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Reconfiguration of Power Distribution Networks by Evolutionary Algorithm for Reliability Improvement

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12th May, 2016

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Department of Electrical Engineering

Contents

1 | Introduction

Through the power system's history, the development of networks have been tremendous. Different scenarios have formed the basis for the development, and these scenarios are changing almost every year. Developments of distribution networks can be characterized by different needs / stages, as illustrated in Figure 1.1 [1].

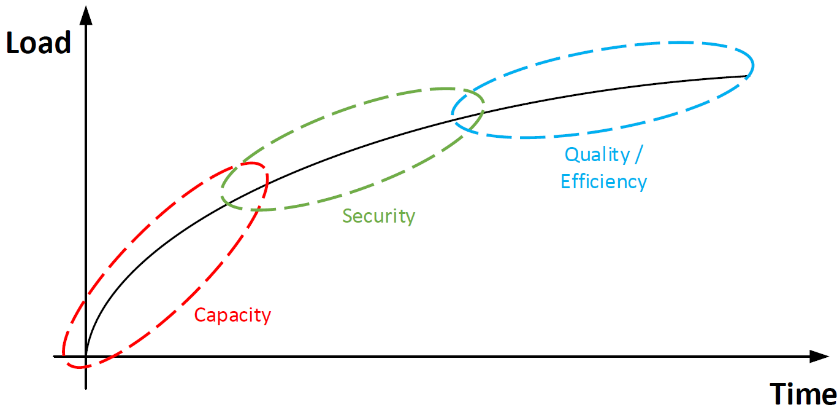

Figure 1.1: Development in needs / stages in distribution networks over time

As illustrated in Figure 1.1, the interest in the start of a distribution network is directed against ensuring enough capacity for the demand. Over time capacity becomes a minor problem, while the security of supply is a new need. Security of supply is of course an ongoing challenge for every distribution utility company, as well as it is for transmission system operators. However, the security of supply has become a more complex part of power systems, since today's security of supply includes several faults and different fault scenarios. This is a development which is in line with the development of tools that are available for analysis of power systems. Same options have not been available in the start of the power systems history. Nonetheless, the security of supply becomes more important as the voltage level in the power system increases, since faults will affect a larger amount of customers.

The level of security of supply is different from each utility company, since the level is based on different grid codes, and utilities own requirements. Nevertheless, security of supply has not been the only interest in the development of distribution networks, as well as transmission networks, in the recent years. A greater focus on optimization of networks that already exists is steadily increasing. This is mainly due to economic perspectives, where utilizing the already existing assets, and thereby improving the quality and efficiency of the network, can potentially postpone investments. Optimization of networks are also known as loss minimization due to reconfiguration of networks, better modelling of networks, load forecasting etc. This are just few optimization areas that will contribute to utilizing the existing network better, and thereby increasing the quality.

The quality of a power system is also known as the reliability, which in the recent years has obtained a greater attention. The reliability of power systems covers lots of aspects in the system, which will be be explained through the report. In this context, this report aims to analyze how losses in distribution networks can be minimized, by reconfigure the switch positions in the network. For this purpose the distribution network will be considered as a 10-12 kV voltage level system.

Minimization of losses is not a power system constraint, however it reduces costs and will in some way improve the voltage level in the entire network. Especially reconfiguration of distribution networks, and thereby minimization of losses, have been one of the optimization investigations in the past years. This is caused by the increased demand of electricity, which is mainly due to renewable energy sources such as electric vehicles (EV) and heat pumps (HP). The forecast of total electricity consumption in Denmark until 2035 can be observed in Figure 1.2 [2].

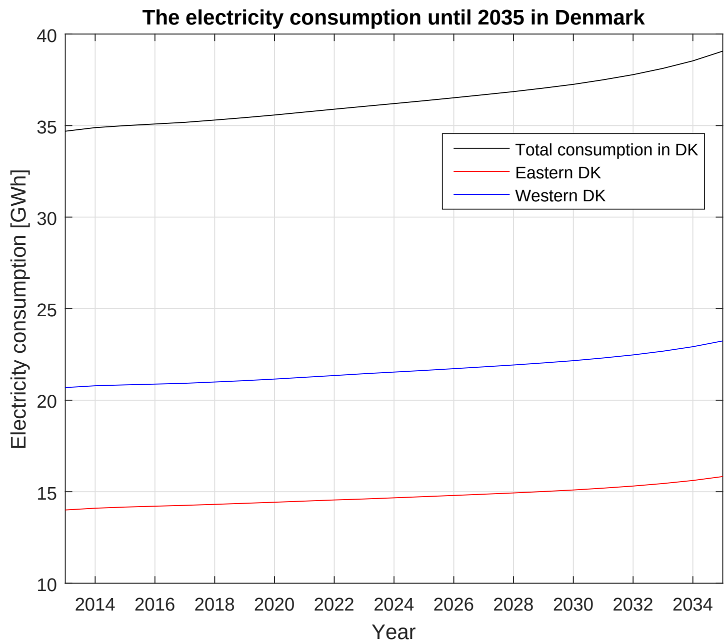

Figure 1.2: Total electricity consumption in Denmark until 2035

The transmission operator in Denmark, Energinet.dk, expects an total increase of around 6.225 GWh in electricity consumption until 2035. The main reason for this increment has to be found in the expected increment in electric vehicles and heat pumps. In addition, from 2013 to 2018 Energinet.dk does not expect any increases in the household electricity consumption. However, from 2018 to 2035 the household electricity consumption is expected to increase with 0.15 % annually.

This increased demand by new renewable energy sources may in some years starts questioning the capacity in the distribution networks. Hence, the interest of needs, and thereby the development in distribution networks, may to some extent restart in according to Figure 1.1. This challenge, among other, the utility companies to optimize the utilization of the already existing networks. This includes minimization of losses by reconfiguring the network, as different supply areas in turn will experience an increased loading level. This will contribute to maintain a certain voltage level, in which complies with the applicable grid codes. Overall, these operational improvements will indirectly affects the customer experience in a positive way, which will be explained further through the report.

Nonetheless, a reconfiguration will contribute to postpone investments for utility companies, where such investments could be extension of the existing network to improve the capacity. Deferment of these investments can be an advantage, since the forecast of electricity consumption by electric vehicles and heat pumps still have uncertainties. Hence, the need of new capacity in distribution networks - following a reconfiguration of the network is carried out - is also potentially unsafe. The expected increase in electricity consumption by electric vehicles and heat pumps until 2035, can be seen in Figure 1.3 [2].

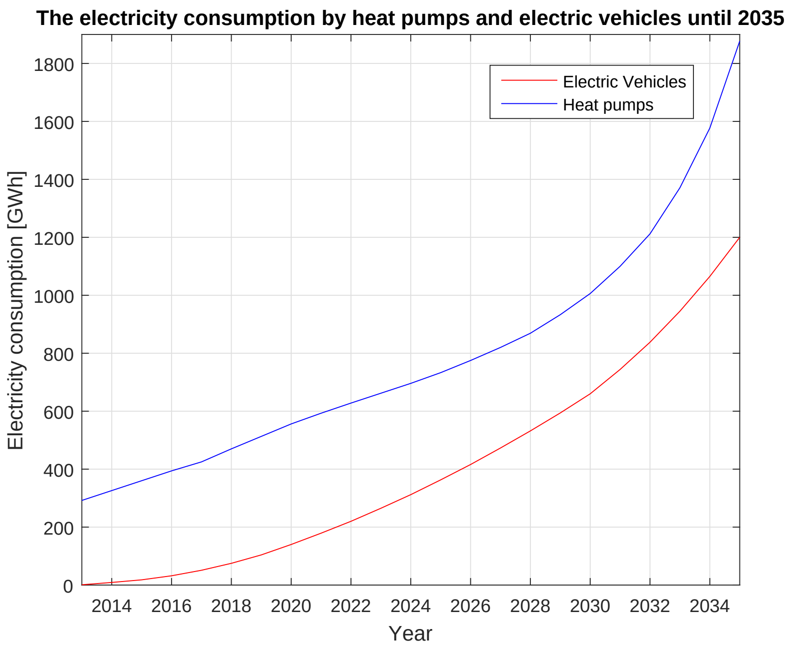

Figure 1.3: Electricity consumption by electric vehicles and heat pumps until 2035 in Denmark

By this prediction Energinet.dk expects 250.000 installed heat pumps in 2035. Among these a mixture of different heat pumps are assumed. Additionally, Energinet.dk expects that 400.000 electric vehicles will exists in 2035. This should be seen in relation to the number of electric vehicles in 2013, which was about 1390.
This increased demand by EV and HP will increase losses in the networks. However, the size of the increase in losses depends among other on the patterns of consumption. These potential problems will be elucidated later in this report, which will analyze possible problems in according to reconfiguration of networks.

Besides that EV and HP implies an increased loading level in the network, the flow direction in the network will still be known. The same is not true when photovoltaic cells (PV) are implemented in the same supply area. Photovoltaic cells are generally an increasing factor in the power system due to the growing number. Expectations from Energinet.dk about the increasing number of PV can be seen in Figure 1.4 and Figure 1.5 [2].

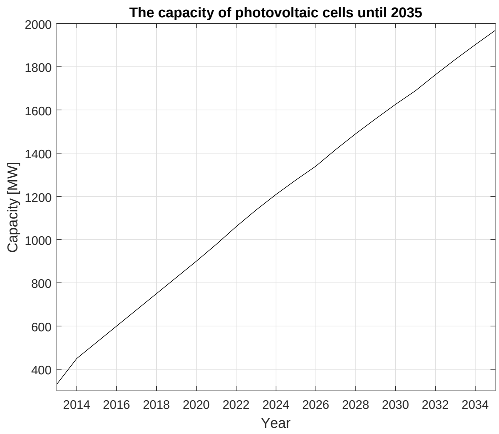

Figure 1.4: Development in the capacity of photovoltaic cells until 2035 in Denmark

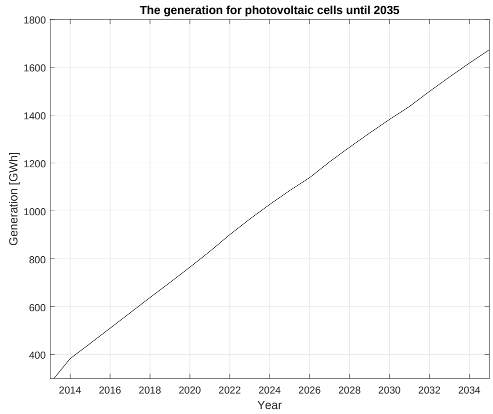

Figure 1.5: Development in the generation for photovoltaic cells until 2035 in Denmark

As indicated in Figure 1.4 and Figure 1.5, the growth in photovoltaic cells are enormous, and should be given attention when networks are optimized by, for example, a reconfiguration of the network with respect to minimization of losses.
However, even though photovoltaic cells introduces a new flow of power in the network, it may not need to question the capacity of the distribution network. If the generation from the photovoltaic cells equals the demand in the low voltage grid, the distribution network will not experience a reversed power flow. In contrast, a reduced loading of the lines in the distribution grid will be observed, which will contribute to a minimization of losses.
In periods of time when the generation is greater than the demand, reversed power flow will be experienced through the distribution transformer (10/0.4 kV). In these situations an increased voltage level along feeders has to be encountered, both in the distribution - and low voltage network, when reconfiguration of distribution networks are executed. Moreover, the reversed power flow may contribute to heavier loaded lines in the distribution networks, which leads to increased losses. As for EV and HP, these considerations depends among others on the production - and consumption pattern. A further description and analysis of these aspects are evaluated later in the report.

In relation to photovoltaic cells, wind turbines are in the same category and must receive the same attention. However, since this report deals with distribution networks, wind turbines becomes a smaller part of the producers in the distribution network compared to photovoltaic cells. Thus, they will not be treated further in this report.

2 | Reliability

Within power system operation the definition of reliability is an ambiguous term. It does not have a certain definition, while it can be interpreted in many different ways. It is a common practice to relate the reliability term in reference to customer interruptions, which indicates how many times in a year customers supply are interrupted due to failures in the network. In perspective to ensure a high security of supply, customer interruptions is a good index, while it is often used to benchmark and maintain competition among utilities. For this comparison the indices: *System Average Interruption Duration Index* (SAIDI) and *System Average Interruption Frequency Index* (SAIFI), are often used, which will be described later in this chapter.

Additionally, reliability can also be related to voltage quality from a utility company perspective. Different grid codes about power quality exists to ensure a reliable power supply for the customers. A high voltage quality can be ensured in many ways, and lots of different factors have impacts on the voltage quality. Among these factors are harmonics, transients, flicker, heavily loaded equipments and too low level of short-circuit capacity. These are all factors that implies a non perfect sinusoidal voltage source. Independently of which factor that is analyzed, utility companies have to solve and optimize the wave form of the sinusoidal voltage source in the most reliable way. Hence, for utility companies reliability of distribution networks also covers optimization of using the already existing network, to ensure a voltage quality that complies with the grid codes. These perspectives can be considered as operational and maintenance of the network, which ensures a satisfactory level of customer interruptions.

From these perspectives the term of voltage quality is a subset of the supply reliability. However, both the supply reliability and voltage quality are overall covered by term of *power quality*. The graphically explanation is shown in Figure 2.1. As indicated, the power quality covers both the supply reliability and voltage quality, which can be defined as:

- *Supply Reliability:*
  Is the availability of supply in a given area, which relates to the number of interruptions, and the duration time of these interruptions. This is primarily described by the indices SAIDI and SAIFI.

- *Voltage Quality:*
  Relates to the quality of the sinusoidal voltage source, which has to comply with different grid codes. Moreover, the frequency in the network is also included as well.

Overall, the supply reliability and voltage quality are subsets of power quality, as shown in Figure 2.1. Power quality must in this connection be viewed as the overall framework, in which contains requirements when building, maintaining and operating distribution networks or power systems in general.

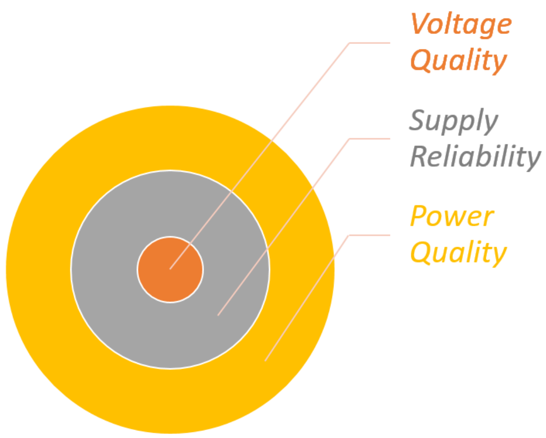

Figure 2.1: Graphically overview of reliability

Both supply reliability and voltage quality contributes to maintaining a satisfactory level of power quality in the network. However, as also shown in Figure 2.1, the voltage quality is a subset of the supple reliability. It is fundamentally important to maintain a degree of voltage quality. This means that the network must be maintained to a certain standard. Thus, if fault occurs the customers can within minutes have re-established the supply. By not considering the voltage quality, it may be challenging to supply customers in case of a fault, which directly impacts the SAIDI and SAIFI, and thereby the supply reliability.
This shows the importance of ensuring a certain level of voltage quality, since it is the foundation to maintain a high supply reliability. Hence, when optimizing networks in reference to the supply reliability, utility companies must first consider the voltage quality. When a network with acceptable voltage quality is achieved, the network can be further optimized to reduce SAIDI and SAIFI. In addition, it has to be encountered that by optimize the voltage quality, it indirectly also optimize SAIDI and SAIFI to some extent. Thus, by continuously maintain and sustain a certain voltage quality, does also contributes to the maintenance of SAIDI and SAIFI at a certain level.

Relating this to reconfiguration of distribution networks, with respect to minimization of losses, it it located within the optimization of voltage quality. By reconfigure the switch positions in reference to reduce network losses, it automatically improves the voltage quality (voltage level) to some extent. However, an improved voltage quality does not directly improve the SAIDI and SAIFI in case of a fault occurs. There may be a line that has a too low capacity, and thereby acts as a constraint in the resupply of the customers after a fault. This line may not have enough capacity, since it in normal operation after the reconfiguration, supply some heavy loads. Hence, the time without supply will be extended, and directly affect SAIDI in a negative way.
In these situations it might also be the case that the total demand in the area is higher than the capacity, while reconfiguration is not enough to sustain a certain power quality. This shows that the interdependency between voltage quality and supply reliability indicated by Figure 2.1 needs to be encountered in the optimization process. These processes are related to the operational- and maintenance processes in the network.

Reconfiguration of distribution networks with reference to reducing losses, is a good example of how utility companies can optimize the already existing network. This are analyzes which not costs greater investments, and these analyzes can be seen as *"picking the low-hanging fruit first"*.

When analyzes as reconfiguration of networks have been carried out, it creates more evidence for larger investments to improve the supply reliability, since optimization of the existing network has already been encountered.
Nonetheless, by contemplating the future increments in HP and EV, which leads to increased loaded lines, optimizations as reconfiguration of networks will be of interest. This is due to the fact that forecasts of HP and EV have uncertainties, and by *"picking the low-hanging fruit first"* can postpone investments to some extent.
Although investments are postponed, the level of voltage quality and supple reliability will initially not be affected to a greater degree due to an ongoing optimization of the network. This safe some time for utility companies, which contributes to making the right decisions for the future distribution networks, in order to improve the reliability and utilization ratio.

2.1 Reliability indices

As already indicated in Figure 2.1, the supply reliability relates primarily to costumer interruptions, and how long these interruptions lasts. *Interruptions* can have different characteristics. It can be due to false trip of relays that creates an open circuit. In the same context, it can be due to fault occurrences in the network, which eliminates the supply path to the customers. On the other hand, *outages*, where equipments are de-energized, does also exist. An outage can be either scheduled or unscheduled. The difference between these is based on if the outage is known in advance (scheduled) or not (unscheduled).

The major difference between interruptions and outages is that customers does not experiences outages, while they experiences interruptions. Thus, when analyzing the supply reliability, it is restricted to interruptions, which can be divided into two categories:

1. *Momentary Interruption:*
   In this case the customers are de-energized less than few minutes. These kind of interruptions often occurs due to automated switching.

2. *Sustained Interruption:*
   In this case the customers are de-energized for more than few minutes. These interruptions are often related to open-circuits or faults.

The boundary between momentary and sustained interruptions is defined in IEEE 1366 standard as being 5 minute(s) [3]. The most common time interval for a momentary interruption is within 1 - 5 minute(s), however a boundary of 1 or 5 minute(s) is not a major difference for the customers. From utility companies perspective, there is a major difference of 1 and 5 minute(s). Within five minutes they will be able to restore the supply, if automated or remotely switches exists in the network. This will not be possible, if the boundary was 1 minute. This have a major impact on SAIDI, since the customers will experience a reduced time without supply. What also important is that if the utility company can restore the supply within 5 minutes, they will not be charged for a sustained interruption, while SAIFI is improved. This will be close to impossible, if the boundary was 1 minute.

By reconfigure the network in the most reliable way, will contribute to restore the supply within five minutes in areas, where automated and remotely switches exists. If the network configuration is far away for being optimal, it might be the case that automated and remotely switches lose their usefulness. Thus, restoring the supply within five minutes will be challenged.

Hence, by reconfigure the network in the most reliable way (reduced losses) will contribute to exploiting the usefulness of the automatic and remotely switches optimally. This is an another perspective of utilizing the already existing assets more optimal, and thereby maintain a certain reliability level.

2.1.1 Customer-based reliability indices

A lot of different reliability indices exists, where the basic indices within customer-based reliability will be introduced and explained through this section. It remains to that load-based and power quality indices are not introduced. This is due to the fact that customer-based reliability indices, are often used as benchmarks and improvement targets for the utility companies [3].

The formulation of the basic customer-based reliability indices, where interruptions refers to sustained interruptions, are given as:

System Average Interruption Frequency Index:

$$SAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Total\ Number\ of\ Customers\ Served} \quad [/year] \tag{2.1}$$

System Average Interruption Duration Index:

$$SAIDI = \frac{\sum Customer\ Interruption\ Duration}{Total\ Number\ of\ Customer\ Served} \quad [hour/year] \tag{2.2}$$

Customer Average Interruption Duration Index:

$$CAIDI = \frac{\sum Customer\ Interruption\ Durations}{Total\ Number\ of\ Customer\ Interruptions} \quad [hour] \tag{2.3}$$

Customer Average Interruption Frequency Index:

$$CAIFI = \frac{Total\ Number\ of\ Customer\ Interruptions}{Customers\ Experiencing\ one\ or\ more\ Interruptions} \quad [/year] \tag{2.4}$$

As it is observed in equation (2.1), *SAIFI* indicates how many sustained interruptions an average customer will experience over a year. From that point of view, the only way to improve SAIFI is to decrease the number of interruptions - where it is assumed that the number of customers are constant. In relation to SAIFI, equation (2.2) shows that *SAIDI* indicates how many hours without supply an average customer will experience through a year. By inspecting the formulation of SAIDI, the only way to improve it is to reduce the number of interruptions - or reduce the duration time of each interruption. This assumes a constant number of customers as well.
Since SAIDI both can be improved by reducing the number of interruptions or by reducing the duration time of the interruption, SAIDI can more generally be used to reflect reliability improvements. Therefore, by reducing SAIDI indicates reliability improvements in general.

Additionally, *CAIDI* does not necessarily reflect reliability improvements. CAIDI indicates how long the duration time of an average interruption lasts. By inspecting equation (2.3), CAIDI can be improved by reducing the duration time of the interruptions, however it can also be improved by increasing the number of interruptions with short duration time. Hence, even though CAIDI is reduced, it can lead to that SAIFI / SAIDI are increased - since an increased number of interruptions have negative impacts on both SAIFI and SAIDI.
Furthermore, a less common used index is CAIFI, which is independent on the number of customer served. This index is only based on the number of customers that have experienced one or more interruptions in the same year. CAIFI is quite similar to SAIFI, however one major difference exists. It is possible to have a SAIFI index with a value of zero, while the lowest possible value for CAIFI is one. In order to improve CAIFI, the number of interruption experienced by one customer could be reduced from 2 to 1 interruptions.

Besides using reliability indices in benchmarks and as improvement targets, they can also be used to decide on investments. However, it is important to fully understand the indices to ensure that investment failures not occurs. How the reliability indices can be utilized and the potential problems behind them, are analyzed in the coming sections.

2.1.2 The usage of reliability indices

Reliability indices are utilized in many analyzes with different aspects. They are often part of historical analyzes, where investigations as fault patterns, operating experiences etc. are of interest. This implies to use reliability indices for predicted analyzes, where it is possible to examine how likely the proposed solution will solve the problem. Overall, SAIDI and SAIFI are two of the most common used indices.
In this context SAIFI is one of the most simple reliability indices due to the intuitiveness. SAIFI describes the frequency of fault occurrences, while SAIFI can be viewed as a function of causes. The background for these causes may be of interest to investigate the conditions of the concerned network. These investigations can be used for further analyzes to determine the factors, in which causes the interruptions. Factors due to increased faults of equipments, cables etc. are often due to age [3]. Therefore, SAIFI can to some extent be directly translated to being an index, which represents the *"health"* of the network. Since SAIFI not includes the duration of faults, grid planners often tend to utilize SAIFI for the future planning of networks. Within the planning of networks, it may be that some scenarios includes elimination of historical bad cables or equipments, which is based on a SAIFI analysis. Hence, future planning projects may be affected by SAIFI, and thereby improve the capacity / voltage level (depending on the problem to solve in the specific area), while in the same time improve SAIFI.

On the other hand, when analyzes have to address the duration of the interruptions, SAIDI is one of the common used indices for such a purpose. This index does not indicates the condition of the network, while it indicates how fast a utility company can restore the supply after a fault occurs. Hence, it is possible for utility companies to introduce new methods / processes, which are thought to reduce the time without supply. Since these new initiatives only relates to improve the duration time, it will not affect SAIFI, while the implementation can be directly related to SAIDI. Therefore, after new processes are introduced, it can by SAIDI be observed whether the new initiatives have improved the conditions. For example could the duration time be minimized by doubling the number of crew members, in which are able to restore the supply. However, this may in the same time be an expensive solution to reduce the duration time, and thereby obtaining SAIDI improvements. Thus, it is possible to utilize SAIDI in some cost-worth analyzes for improvements, which may be very useful for the decision-making process in utility companies.

2.1.3 The interdependence between reliability indices and potential problems

For every utility company goals regarding reliability indices exists to some extent. These goals can either be based on a single index, while it can also include multiple indices. Furthermore, the reliability indices can exist for each voltage level, different areas, the entire system etc.

The challenges of having multiple indices are not to set performance goals for each of the indices. It can often be an advantage to have several indices to follow the development over time. This can provide a good overview of the tendency in the reliability level in the network over time. However, in accordance to adoption of resolutions, it may be challenging to have several indices compared to have a single reliability index. By only considering e.g. SAIDI, each new proposed project can evaluate the potential improvements in SAIDI by a cost-to-benefit ratio. This attributable to evaluate DKK per. SAIDI minute, which is a useful ratio in relation to the process about deciding, which projects that have to be selected.
When operating with several indices, it is often the situation that an improvement in one of the indices, leads to improvements in other indices to some extent. Thus, the decision making process regarding selecting projects that improves those reliability indices, in which have performance targets, becomes an optimization problem. It is often the case that several utility companies imposes SAIDI as being the only reliability indices for the decision making process [3]. Thus, a cost-to-benefit ratio relates to DKK per. SAIDI minute reduction.
The relationship between SAIDI and SAIFI is already well-known, while improvements in SAIDI can also indicate improvements in SAIFI without using the index. The level of improvements in SAIFI as a result of improvements in SAIDI, will ultimately be decided by whether the customers are willing to pay for a reduction in interruption time of e.g. one minute or one hour. If one hour interruption is valued the same as an two hour interruption, SAIDI improvements will not be a good indicator for SAIFI improvements. However, if one and two hour interruptions are valued differently, SAIDI will be a good indicator for improvements in SAIFI as well.

Value Based Reliability Planning
Generally, it has been shown by experiences that investments based on SAIDI leads to improvements in SAIFI as well, which is due to that these indices are interrelated [3]. Therefore, SAIDI can be a good estimator when future investments have to be made. This way of planning is also known as *value based reliability planning*. By this means that utility companies can based on measuring of reliability indices, in which represents customers' experiences, economically decide new investments-, operations- and maintenances projects. The overall aim for value based reliability planning is to ensure:

1. Against an excessive level of investments that leads to an increased reliability level that customers are not willing to pay for.

2. Against an excessively low level of investments that leads to increased number of interruptions (reduced reliability level), in which the customers are not willing to accept.

From a utility company perspective, it is a delicate balance to find the right investments. Therefore, by implementing SAIDI / SAIFI in project decisions or in optimization problems (e.g. reconfiguration of distribution networks with focus on minimization of losses), contributes to find the right balance between potential investment costs and economic consequences by interruptions.

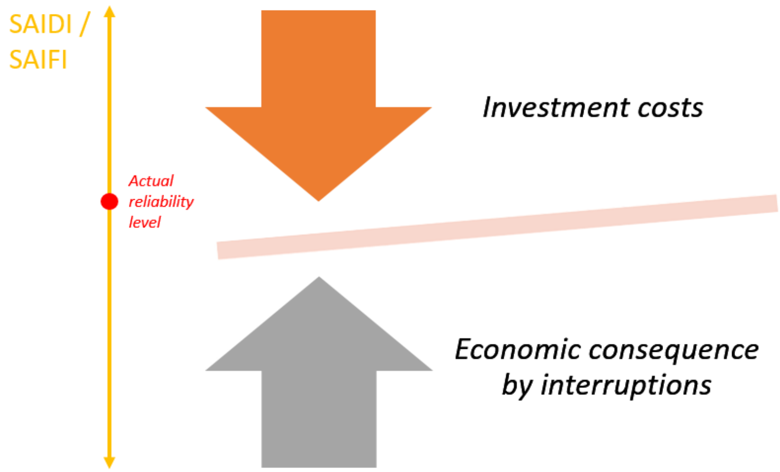

Figure 2.2: Balance between investment cost and reliability level

As indicated by Figure 2.2, the investment costs and economic consequences have strong impacts on the reliability level. The economic consequences both exists for utility companies and customers. The utility company lose potential energy sale, while costs related to restore the supply (repair cables etc.) also needs to be considered. For customers the costs can be related to lost production (mainly industrial customers), while residential customers relates "*costs*" to the hassle of interruptions.
By lowering the number of investments or taken wrong investment decisions etc. may affects the number of interruptions to increase. This will imply the economic consequences to increase, and thereby increase the reliability indices. This negative development can be slowed down by new projects, which thereby leads to new investment costs for the utility. This produces the opposite effect in accordance to Figure 2.2, and thereby reduce the reliability indices. Thus, if the reliability indices are too high for either industrial or residential customers, it is related to increased economic consequences. This will further appears to raise the level of needed investments costs for the utility in accordance to Figure 2.2, in order to maintain the reliability at a certain level.

Therefore, the value based reliability planning aims to find the balancing between the costs for a utility, and the benefits gained from these costs. The total cost is thereby a composite size of the investment costs, and the economic consequences which the customers experiences. The total cost can graphically be shown as in Figure 2.3, which shows how the system reliability affects the costs for both the customers and utilities. By increasing the the reliability level (reducing SAIDI / SAIFI) leads to new investments for the utility, while the economic consequences for the customers decreases. The opposite happens if the utilities decreases the system reliability level, which leads to fewer investments, and thereby a reduced cost. This will on the other hand increase the economic consequences for the customers, which might be unsatisfactory.

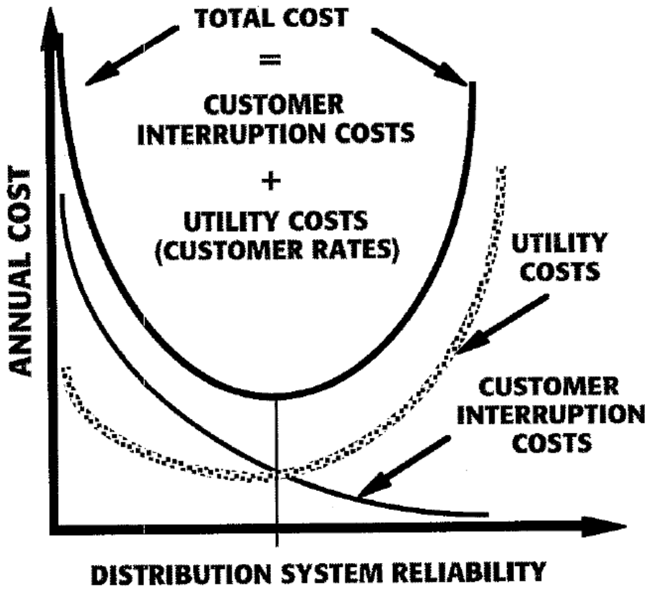

Figure 2.3: Total reliability cost [8]

Nonetheless, a global minimum at the total cost curve exists, which may be the aim for utilities, in order to keep the costs and satisfied customers at a certain level. However, by optimizing networks with the assets that is already available, can keep the reliability level at a certain level for a given period. This is relevant with perspective to minimization of losses, since it improves the conditions in the network, and thereby indirectly improves the reliability level to some extent. This optimization implies to decrease the size of economic consequences, since the customers will experience interruptions with a reduced duration time due to improved conditions in the network. Hence, the potential investment costs can be postponed, which is valuable from a utility company perspective. It may also be the case that the optimization process have solved the specific problem, while investments are not a requirement any more in a perspective of 10-20 years. As already mentioned, this optimization process make use of taking the "*low-hanging fruit first*", which should be considered as the first option to optimize the balance indicated in Figure 2.2 and Figure 2.3, before any investments decisions are made.

Potential problems
Although reliability indices are useful to both measure the performance of the reliability level in networks and to choose projects, there is a potential risk for incorrect decisions occurs in accordance to which projects that are selected. Thus, these wrong decisions will lead to wrong investments, in which are not in line with the customers interest.
Especially the number of customers have a major influence on both SAIDI and SAIFI with reference to equation (2.1) and (2.2). Therefore, projects that involves a larger number of customers, will often experience larger improvements in SAIFI and SAIDI, compared to projects which concerns a minor number of customers. This leads to that areas with a larger number of customers would be preferred in the project selection, compared to areas with a smaller number of customers.
Nonetheless, areas with a larger number of customers often have a reliability level that are better than average [3]. The opposite appears for areas with a minor number of customers, which often have a reliability level below average. Hence, by not being critical to SAIDI and SAIFI, it can lead to project selections (potential investment failures), which prefer areas with a larger number of customers, even though that the level of reliability is better

than average.
Nevertheless, SAIDI and SAIFI are fundamentally good reliability indices, which can indicate the actual level of reliability. They can be good as project decision tools, while they can also lead to investment failures. This is why they should be interpreted with some caution, when they are utilized within projects.

2.1.4 Mathematically Formulation of Reliability Indices

Due to the growing concern regarding reliability indices utilities, reliability indices have become a part of objective functions. Depending on the objective, the usage of reliability indices can be very different from problem to problem.

This report will not implement reliability indices into the objective function, while it only focus on minimization of losses. However, further development in this optimization process could be to implement reliability indices that both encounter minimization of losses and reliability indices. Therefore, as an example SAIDI can mathematically be expressed by equation (2.5) [9].

$$SAIDI = \sum_{i=1}^{n_i} \sum_{j=1}^{n_j} \frac{\lambda_i \cdot r_i \cdot N_j}{N_{total}} \qquad [hour/year] \tag{2.5}$$

Where:

- n_i: Is the number of outage events.
- n_j: Is the number of nodes without supply due to the outage i.
- N_j: Is the number of isolated customers due to the outage event i.
- N_{total}: Is the total number of customers in the network.
- λ_i: Is the average failure rate of outage i.
- r_i: Is the average interruption duration time of outage i in hours.

As it can be observed, statistical data of the average failure rate and interruption duration time are required in order to implement SAIDI as one of the terms in the objective function. This makes greater demands for the utilities to maintain the data base about defects and failures in the network in reference to optimize the network operation (losses, voltage level etc.).

3 | Loss Optimization in Distribution Networks

This part of the report deals with how loss optimization can be described mathematically. The loss optimization will be based on reconfiguration of networks, by changing the status of the switches.

The opportunities within changing the status of switches changes from network to network. There may be substations in the network where switches not exists, while a bolted connection exists instead. In those situations it is impossible to sectionalize the network, which have to be considered through the optimization process. In general, two different types of switches are defined:

- **Tie switches:** Is generally kept open in normal conditions.
- **Sectionalizing switches:** Is generally kept closed in normal conditions.

In the optimization process the aim is to move the tie switches, in which cause a reduction in losses. Despite this purpose, the optimization has to encounter that the topology of the distribution network is a radial configuration. Hence, loops in the network should be avoided through the optimization process. Additionally, the given voltage limits and line capacity limits should also be taken into consideration. The implementation of the explained considerations will be examined through the next sections.

3.1 Radial configuration

Radial network configuration is a common used topology for distribution networks. This configuration contributes to clarity in connection with the search for faults, while it is also easy to protect. On the other hand, the topology allows to have back-up supply by the neighbouring feeders, which increases the security of supply.

From each primary station, which transforms the voltage to 10 kV, several feeders exists, which in normal condition supplies several substations. In some of the substations, tie switches exists to sectionalize the network into a radial network configuration. It is also from the substations that the customers are fed through a distribution transformer (10/0.4 kV). Two examples of common radial configured networks are introduced in Figure 3.1 and Figure 3.2.

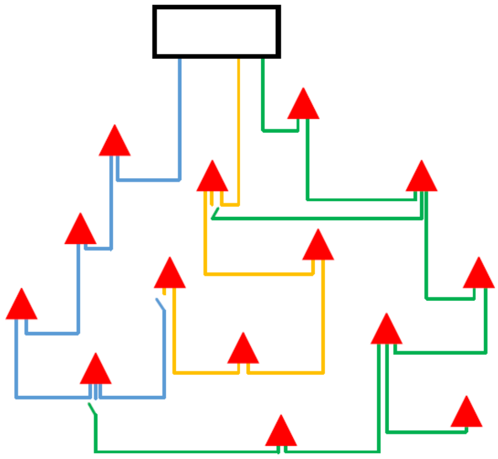

Figure 3.1: Radial network supplied from only one station.

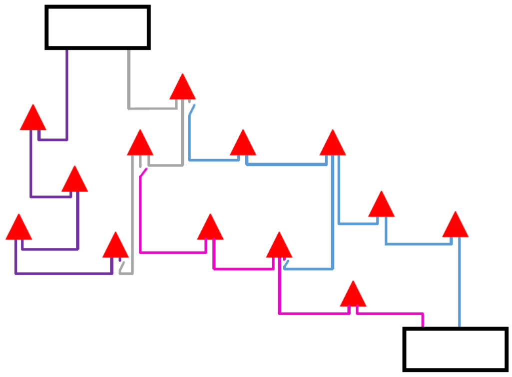

Figure 3.2: Radial network supplied from two stations.

In both figures, the red triangles symbolizes the substations, while the black rectangles symbolizes the primary stations. Each feeder in both figures have been coloured individually. Thereby, at the points (substations) where the colour changes indicates a tie switch. The sectionalizing switches are not visible due to that they are normally closed. It may be observed that a satellite substation exists in Figure 3.1 (lower right corner), where it may be the case that a bolted connection exists. A switch in this situation is not necessary.

In both figures it can be observed that a faulted feeder can be resupplied by one of the neighbouring feeders. When the radial network is constituted of feeders from more than one primary station, it will to some extent have a higher security of supply. If the supply to one primary station fails, the substations will not be supplied in Figure 3.1, even though interconnections between the feeders exists. However, if one of the primary stations fails in Figure 3.2, the feeders from the neighbouring primary station have the opportunity to restore the supply to some or all of the feeders without supply (depending on the capacity in the network).

In accordance to the optimization process, it is extremely important to ensure radial configuration in the network. This is due to the fact that loops will create a higher short-circuit level, which the equipment may not withstand. Furthermore, equalization currents between primary stations may arise, which is not preferable. The protection system may also be challenged, and many unnecessary customers may experience lack of supply due to bad selectivity. Hence, a significant factor in the optimization problem is to maintain the radial configuration.

3.2 Potential issues with reconfiguration of distribution networks

In optimization problems it is important to recognize the limits, in which have to be considered in the search process for the optimal configuration. It is already known that grid codes exists, which limits the voltage level. From a utility company perspective, it is also important to secure against overloaded equipments, which can result in faults and / or reduced life time expectancy. These constraints are commonly subjected to the objective function, while the following subsequent headings have been found as additional potential issues, in reference to reconfiguration of distribution networks.

- Increased voltage due to increased impedance from the primary station to substations with generation installed (e.g. photovoltaics).
- Problems of compliance with the reserve supply (n-1).
- Dynamically changed loading profiles, which is also affected by the increased amount of EV and HP.
- Facility with limitations.
- Possible risk of minimizing the short-circuit level, which could affect the protection of the network.

The above mentioned items have a common characteristics; they does not describe a limitation of a certain equipment. However, they impacts that there may be problems to comply with the grid codes - or with the line capacity. Each item will be explained separately, and in the same sequence as stated above.

3.2.1 Increased voltage level

The estimated increment in photovoltaic cells in the introduction will to some extent increase the voltage level in the distribution - and low voltage network. Additionally, small wind turbines will also contributes to production in the low voltage grid. However, the reversed power flow through the distribution transformers will also affect the loading level of the cables in both networks.

The distributed production in the distribution network may lead to an overall reduction in loading of cables etc. Meanwhile, it could also be the opposite case, where reversed power flow exceeds the capacity of the cables. However, reversed power flow will cause an increased voltage level, which has to be given attention. This is due to the fact that requirements regarding the voltage level in grid codes exists.

Areas with large distances compared to areas with small distances (measured in impedance), are the most exposed areas in terms of increased voltage levels. Hence, in the process of reconfiguration of networks, it might be the case that the distance from the primary station to the substation, with generation installed, is increased. This increased impedance will increase the voltage in both the distribution - and low voltage network, when the generators are producing.
In order to investigate the impacts of increased impedance in the distribution network after a reconfiguration, a fictitious low voltage network is established, where all the customers connected have a three phase photovoltaic system of 3 kW. The low voltage network is shown in Figure 3.3.

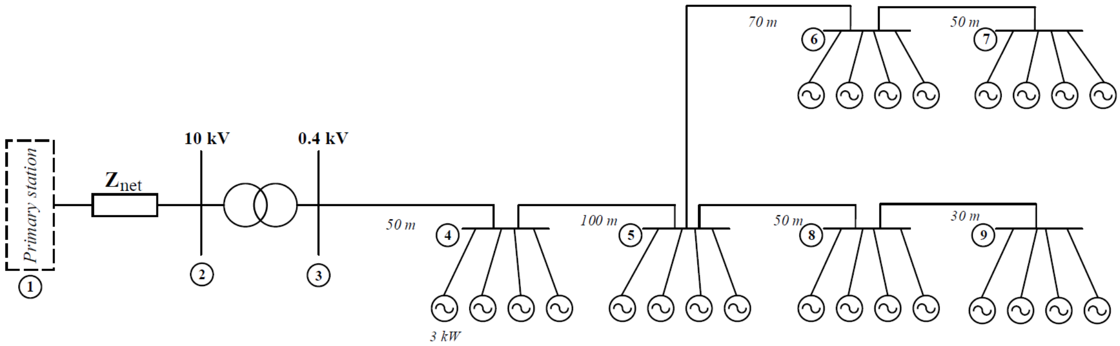

Figure 3.3: Overview of the low voltage network

As shown in Figure 3.3, the low voltage network contains six busbars with four customers connected at each of these busbars. This gives 24 customers in total. It is assumed that no load exists in the network, while full production from each photovoltaic system is the case. This leads to a overall production of 72 kW in the low voltage network. This will give the worst case in relation to increased voltage level in both the distribution network (busbar 2), and in the low voltage network.

It is assumed that the transformers capacity is 400 kVA, and all cables in the low voltage network are assumed to have the type: 95 mm^2 ALPEX. Additionally, the cables in the distribution network are assumed to have the type: 150 mm^2 ALPEX. The distribution network impedance equals to Z_{net} given in Figure 3.3. For simplicity it is assumed that the 24 customers in the low voltage, are the only ones connected to the feeder in the distribution network. Hence, other loads or generators in the distribution network are neglected.

To experience the changes in the voltage level, in reference to increased impedance in the distribution network (Z_{net}), the given network in Figure 3.3 has been build in PowerFactory. An overview of the network in PowerFactory can be viewed in Appendix A. The impedance in the distribution network has been varying in the interval of 1 km, 5 km, 10 km and 15 km. The voltage profile in the low voltage network for each case can be observed in Figure 3.4.

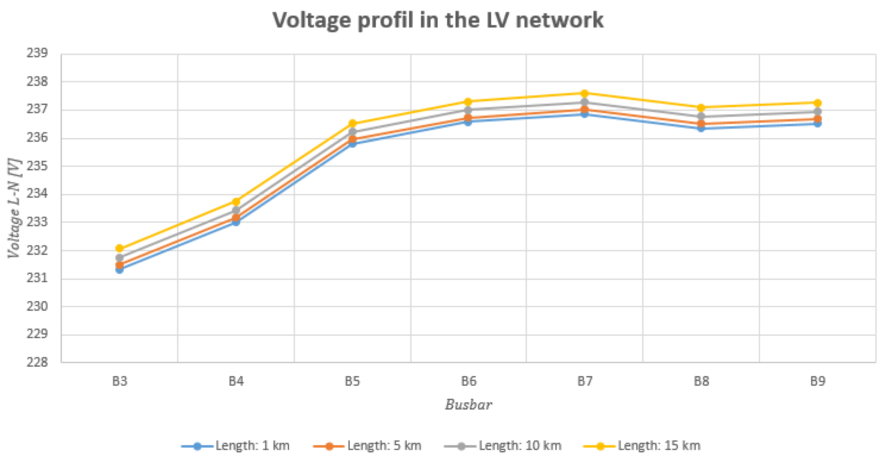

Figure 3.4: Voltage profile in the low voltage network with changed distribution impedance

As it can be seen in Figure 3.4, the changes in impedance in the distribution network have not any significantly impacts on the voltage profile in the low voltage network. Although there is no load in the network, but only production from 24 photovoltaic systems, the voltage levels in the network are not critical.
This should be seen in relation to the requirements for the voltage level of electricity supply. In Denmark the followed standard is DS/EN 50160, which describes the characteristics of the voltage in the public electricity networks - including power quality. This standard specifies that the rms value of the voltage measured as a 10 minute average, should be within ± 10 % of the nominal voltage ($U_n = 230V$). Based on this requirement, the voltage level is acceptable up to 253 V. Compared to the results in Figure 3.4, the estimated voltage levels by the simulations are far away from this upper limit. Hence, from a reconfiguration perspective, an increased length to substations with generations installed is not a problem.

Moreover, the development in the voltage at the primary side of the distribution transformer (busbar B2) can be observed in Figure 3.5.

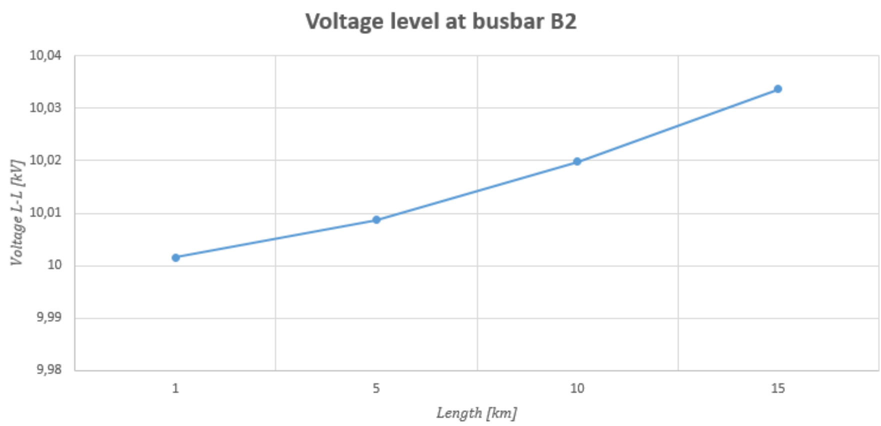

Figure 3.5: Voltage level at busbar B2 with changed distribution impedance

As for the voltage level in the low voltage network, it is observed in Figure 3.5 that the voltage level in the distribution network appears not to critical as well. Additionally, it has to noticed that this analyze only includes a distribution network with one substation. If several substations exists, where all have a certain amount of generation installed in their respective low voltage networks, the voltage level in the distribution network will increase as well. However, by considering the requirements in DS/EN 50160, the upper limit in the distribution level will be 11 kV ($U_n = 10kV$). Hence, it seems not to be problematic with the voltage level in the distribution network in reference to reconfiguration of distribution networks.
Therefore, a high density of distributed generation in one area is needed, before over voltages is a problem, which must be taken into account. In these cases the capacity of the distribution network, as well as the capacity of both the distribution transformer and low voltage network, can be questioned. This type of areas can be definitely be expected in the future by considering the anticipated increment in renewable energy sources made by Energinet.dk. However, this report will not further consider scenarios of areas with a high density of generation.

3.2.2 Reserve supply (n-1)

As explained in the introduction, the security of supply is an ongoing topic for utilities. They have all set their own goals for security of supply, when they plan changes in the network or establish new network areas. One of the commonly utilized criteria for grid planners regarding security of supply is the *n-1 criteria*. By this means that even though a component failure occurs, all customers must be supplied. They will according to the fault lose the supply, however they should within a short time be resupplied by using some neighbouring feeders. How long it should take depends on the utility company and their planning criteria. These criteria depends among other things on the target that the utility has about SAIDI or an another reliability index.
It might be the case in many situations that all customers can be resupplied within 20 - 30 minutes after a fault. However, it might also be the case that this will take several hours before the supply is restored. This extended period of time is caused by a bad configuration of the radial network, while it might has to be totally reconfigured before the restore of supply can be obtained. In this context, *"bad"* means poor utilization of the network in terms of the load distribution among the feeders. In other words: *"bad"* location of the tie switches.
Eventually, several hours will not be satisfactory for customers. Thus, constraints regarding how many neighbouring feeders that must contribute to restore the supply can be created, which is one opportunity among others. This will to some extend limit the time to check, whether the n-1 criteria is met or not, while it also contributes to reduce the time before the supply is restored. Additionally, it also contributes to observe if a optimization of the network is needed. If the n-1 criteria can not be met with a certain number of neighbouring feeders, a reconfiguration of the normal conditions could be performed. If this not solves the problem, investments to improve the conditions, in accordance to the utility company's own requirements, may be the final solution.

On behalf of this approach, the n-1 criteria ensures a certain level of security of supply, which contributes to keep the reliability of the network at a certain level.
Nonetheless, by reconfiguring the distribution network in reference to minimization of losses, it should not lead to a new configuration of the network, in which not complies with the n-1 criteria. In this context, it can be that the new network configuration lead to unacceptable voltage levels or overloaded components in reserve supply (n-1).
This issue can be challenging to subject to a objective function as a constraint. Some articles (e.g. [10]) have implemented a load balancing constraint, in which minimize the losses with respect to that the total current at each feeder should be as close as possible to each other. Intuitively, this may contribute to an increased probability of that the n-1 criteria can be met. By balancing the load the optimization process does not results in feeders, in which predominantly supplies a major part of the network with respect to other neighbouring feeders. By having predominantly equal loaded feeders, it might contribute to minimize losses in normal condition, and additionally avoid both too low voltage levels and too overloaded components, when restoring the supply after a fault.
Nevertheless, this issue have lots of factors that will contribute to whether it is a problem or not in the specific case. On the other hand, the optimization process regarding only reducing losses, might appear to not contribute with problems to the reserve of supply, since reducing losses might balancing the loads between feeders in a sufficient way if fault happens. This potentially problem will not be further analyzed or implemented in the optimization process, since larger networks needs to be optimized in order to analyze the n-1 criteria. This is necessary to provide evidence about this potential problem.

3.2.3 Loading profiles

In general, the objective is to minimize network losses as much as possible over a year. This challenges the specific time stamp, and thereby the loading in the network, in which the reconfiguration should be based on. Several approaches to determine the time stamp can be used, where the approach could be:

1. Find the time stamp where the maximum peak load appears for a given year. The reconfiguration will be performed once on behalf of the chosen time stamp.

2. Find the time stamp which represents the average load over a year, and perform a reconfiguration of the network for the whole year.

3. Divide the year in the four seasons and perform a reconfiguration four times each year. For each period, the chosen time stamp could e.g. be based on the maximum load or a mean value of the load observed in each period.

4. Divide the year into two parts; summer and winter time. Thereby, a reconfiguration is needed twice annually. The chosen time stamp for each period could once again be based on the maximum peak load or a mean value of the load.

The above mentioned proposals are just few out of many different approaches. However, they have all one thing in common; they does not guarantee that the losses are minimized as mush as possible over a year. This uncertainty is due to the estimation of load profiles that occurs in the concerned area. It is quite important to know whether the area only contains residential customers, or if industry customers also exists. Since different kind of both residential customers and industries exists, this deviation might also be important information, in order to approach the right time stamp for the reconfiguration.

Estimations of load profiles have not in the last few years become an easier problem to solve, since the amount of heat pumps, electric vehicle and photovoltaic cells have increased. This problem will not be easier in the coming years, as already indicated in the introduction by the estimations carried out by Energinet.dk.

Estimation of load profiles for HP and EV
Estimation of the individual load profiles for new demands as heat pumps and electric vehicles are very challenging, since the load profiles depends on each individual's needs and way of life. Nonetheless, the goal in relation to network planning is not to predict perfectly loading profiles for each customer (household, industry etc.), and thereby obtain a specific loading profile / characteristic for each customer. The goal within network planning is to see it in a wider context by aggregating load profiles for a larger amount of customers connected to the network. However, this goal still needs knowledge of how the patterns of consumption in most cases will look like.

From a reconfiguration perspective, it may not be the maximum peak load, which is of interest when the aggregated load profile is modelled. For at grid planning perspective, the maximum peak load is naturally of interest, since the security of supply must be ensured. However, by performing a reconfiguration of the network based on the maximum peak load, does not necessarily lead to the maximum reduction in network losses over a year. This is due to the fact that reconfiguration of networks have to be executed for the optimization of operational conditions of the network, and thus ignores the criteria in planning new networks.

Therefore, when dealing with reconfiguration of networks, the process should be based on a time stamp, which generally represents a high load. This will lead to the maximum reduction in losses, while it also contributes to obtain the largest improvements in the operational conditions (voltage etc.) measured over a year.

On the other hand, this does not secure that any limits in the networks are not exceeded. In this context, it might be impossible to find, for instance, four different time stamps in a year, which both secure the highest reduction in losses, while it also ensure against exceeded limits. This is mainly due to uncertainties in the load profiles. Hence, a new suggested network configuration might need to be evaluated for each hour at each day for a whole year, which is based on the estimated load profiles. This analyze may for example include four different reconfiguration suggestions (based on four different time stamps), which can be compared to the following parameters:

- Does any equipments experience overload?
- Does the voltage (especially at the end of the feeders) experience unacceptable voltages in accordance to the grid codes or the utilities own requirements?
- If the two above mentioned requirements are met, which of new configurations leads to the maximum reduction in network losses?

By this approach, concerns regarding overloads and unacceptable voltage will to some extent be avoided, while it can not be 100 % guaranteed due to the uncertainties in the load profiles. However, in order to predict the reconfiguration, in which both complies with the network requirements and maximum reduction of network losses, several time stamps may be compared. This approach is mainly due to the uncertainties in the load profiles for each customers, but also the variation from area to area. Although a normal household look alike from the outside on the perspective of a large city or in the countryside, there may still be differences in patterns of consumption - and maybe also in the size of consumption. Nevertheless, this approach places high demands for estimating the load profiles for each group of customers, since there is a need for a load profile for each hour of each day over an entire year.

On the other hand, this mentioned approach also reduces the reconfiguration of networks to be performed maximum once a year. This is an advantage instead of having to reconfigure networks according to the seasons, as mentioned as a possibility at the beginning of this section. By reducing the number of reconfigurations, the lifetime of the breakers will be extended. This is also an expense that should be included in the equation, when evaluating the reconfiguration strategy, if a reconfiguration is carried out several times in a year.

Based on the above viewpoints, load profiles seems to play a major role, and they will not gain a minor role with an increasing number of heat pumps and electric vehicles. In addition, photovoltaic cells should also get attention, since they also affects the load profiles to some extent. However, the production curve from PV in corporation with EV and HP will not be further considered. In order to encounter the impacts from PV on aggregated load profiles, the analyzes should be carried out in a larger perspective, which should includes larger network areas. It is expected that the PV in the start will cause capacity and voltage problems in the low voltage network (including the distribution transformer), before capacity and voltage problems occurs in the distribution network. By utilizing the method of simulating a new network configuration for each hour at each day over a whole year, will take production into account, while potential overloaded lines and over voltages caused by PV will be avoided to some extent.

Therefore, an example on future load curves for heat pumps and electric vehicles will be given. These will be compared to see a composite consumption curve, which will be based on only one customer.

- **Heat Pumps:**
  The demand of the heat pumps are strongly dependent of the usage of the heat pumps. Does they only contributes to space heating, or does they also contributes to hot water? Another question can be related to whether the heat pumps are for industrial or household usage. These factors impacts the load profile. Additionally, the electricity demand by the heat pumps will also vary in accordance to the seasons, where the demand is expected to rise as the temperature outside drops. This is also shown in a analysis of 10 household (10 heat pumps) for a whole year, which both provides space-heating and domestic hot water [4]. The average electricity demand for each season during 2010 can be investigated in Figure 3.6.

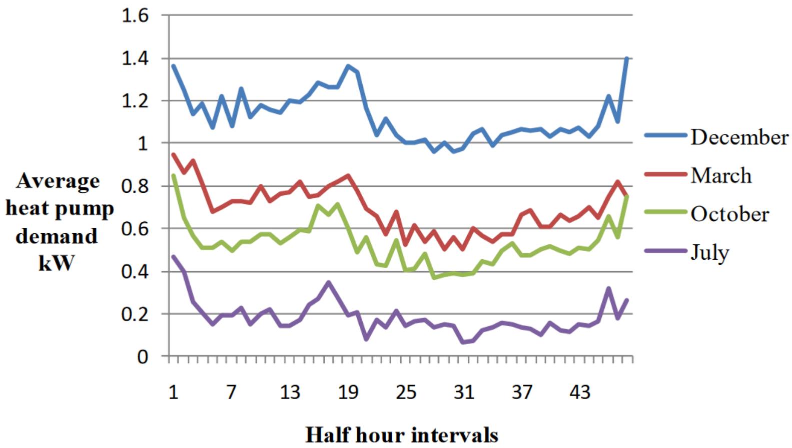

Figure 3.6: Average demand by domestic heat pumps during 2010 [4]

As it can investigated in Figure 3.6, the demand over an average day looks to be fluctuating. Nonetheless, it can to some extent be viewed as a constant demand. This makes sense due to the fact that the heat pumps through the day needs to keep the temperature in the room and water at a certain level. In Figure 3.6 the peak seems to occur around 8-9 am, which can be related to the needs of hot water. Moreover, it can be observed that the average demand increases as the temperature drops outside, since the demand in July (summer month) is more than halved compared to the demand in December (winter).

Furthermore, it is observed that the average demand in March and October are close to each other. This could indicate that most of the months over a year have a mean heat consumption either similar to March or October. This is of interest in accordance to reconfiguration of networks, since this contributes to base the reconfiguration process on time stamps within months close to March or October (if the concerned network area have several HP installed). Since the objective is to reduce losses as much as possible over a year, it is important to find time stamps, where the load is generally high for a longer period. This should be compared to time stamps, where the load is extremely high, but only for a shorter period. Hence, if a network area has a large amount of HP installed, the loading level will gain an offset. This offset may contribute to have generally high loaded periods / time stamps, which is close to March and October. Thus, these months could be the basis for finding time stamps to a reconfiguration of networks with HP installed.

- **Electric Vehicle:**
As for heat pumps, it is challenging to estimate the load profile for charging electric vehicle, since several factors may affect the load profile. Among these it can be mentioned:

  1. Is the car privately-owned or business-owned?
  2. Does special electricity tariff exist, in which may lead to favourable moments to recharge?
  3. Is the electric vehicle fully discharged, when it has to be recharged?

Several analyzes have been made on this topic. By looking at the load profile to recharge electric vehicles, which are used in either business or private respects (and no special information regarding tariff etc. are available), the load profile is expected to be as shown in Figure 3.7 [5].

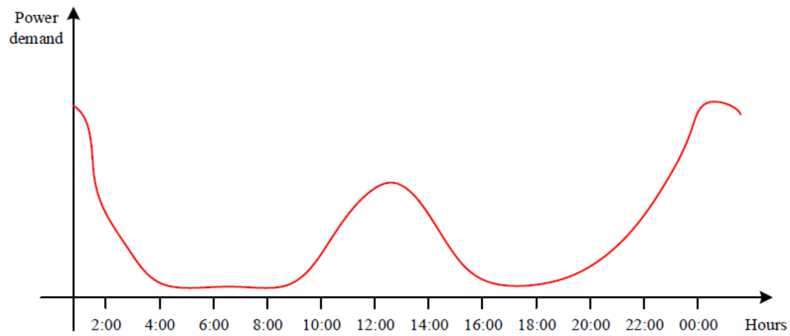

Figure 3.7: Estimated demand curve for charging electric vehicles

In general, two peaks might be expected in the load profile for charging electric vehicles in the future. The first peak appears at noon, when all have been driven to work etc. and need to recharge the electric vehicle before leaving work etc. The second peak appears at night, when all have came back from work etc., and need to recharge the electric vehicle for being ready to use next day.

Compared to the load profiles for heat pumps, the load pattern by electric vehicles are more momentarily, and does not contributes with a constant load, as it is with the heat pumps in Figure 3.6. Moreover, the load pattern by electric vehicles does not change significantly in size with respect to what season it is in the year. Hence, electric vehicles does not contributes to consider specific months over a year, when reconfiguration of the network has to be performed. However, it might be that the increased load at noon or night leads to new time stamps of interest, in which should be considered in the reconfiguration process.

Although electric vehicles may not contributes or have significantly impacts on the configuration of networks (which reduce losses), it might challenging the loading level of equipments (cables etc.) at certain hours. This is why it is important to simulate a given configuration of the network for each hour of each day over a whole year. This contributes to ensure against overloading, and thereby reduced lifetime of equipments, increased failure rate etc.

- **Household:**
  Load profiles from households can be significantly different, which is due to different life styles, apparatus etc. Consumption data in 2011 from one house (in Jutland, Denmark) have been investigated, where it have been found similarities in the consumption pattern in the four weekdays: Monday, Tuesday, Wednesday and Thursday. However, Friday, Saturday and Sunday differs from the rest. This is not surprising, since these days might be more randomly in accordance to customers behaviour.

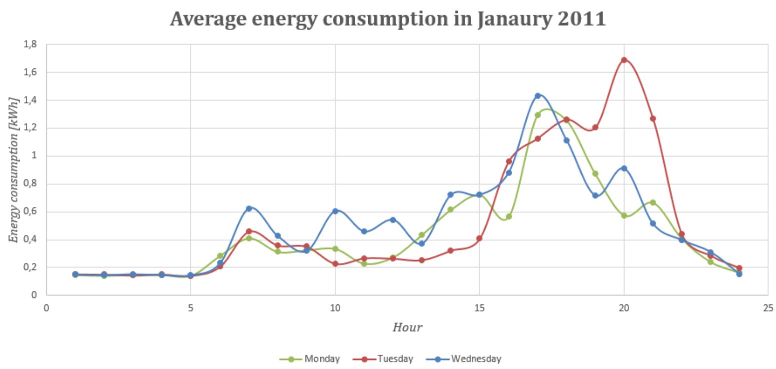

Figure 3.8: Average energy consumption for week days in January 2011

In Figure 3.8 the average energy consumption for three different days in January are shown. As expected there are increased energy consumption in the morning hours before work etc., while the increased energy consumption are also experienced in the afternoon after work.

By assuming the customer invests in both a heat pump and a electric vehicle, an estimated load profile for one day in January can be made. It is assumed that the heat pump have a load profile as shown in Figure 3.6 with a peak value of 1.4 kW. On the other hand, the electric vehicle is assumed to recharge with a peak of 6 kW, which is constant through the whole recharge period. Additionally, it is assumed that the customer drives to work, while the peak shown around at noon in Figure 3.7 is not considered. Thus, recharge in the afternoon is considered.

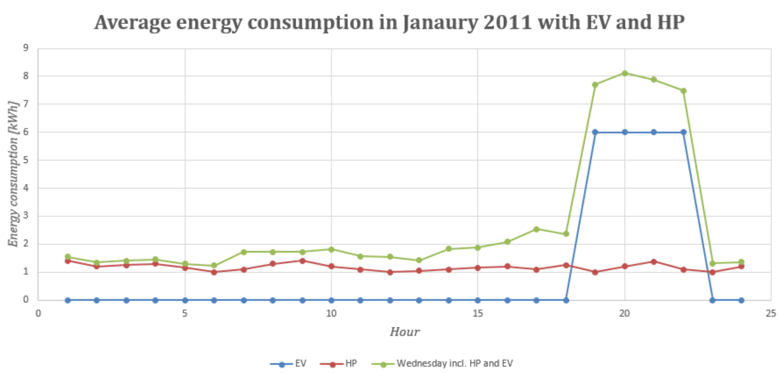

Figure 3.9: Average energy consumption for with EV and HP

Besides that Figure 3.9 shows a fictitious established estimate of consumption on a Wednesday in January, it indicates that the consumption has gained an offset. This general increase in consumption leads to increased losses over the whole day, while

Figure 3.9 shows the importance of optimal configuration of networks in the future.

Nonetheless, the expected increase in consumption may also challenging the capacity of the network. Especially the peak generated by the electric vehicles may be challenging. This peak will just increase by the increment in number of electric vehicles in certain areas.

When dealing with reconfiguration of networks, the experienced peak by the electric vehicles shows the importance of ensuring against overload. Hence, it might seems obvious which time stamp that should be the basis for a reconfiguration process. By choosing the the peak around 20 pm, overload and unacceptable voltage could be avoided. However, this may not over a year lead to the maximum reduction of losses. Moreover, this case only consider one household. By considering several customers, the total load profile in an area becomes more complex, and there may be two peaks for a day. This shows that if the probability of ensuring against overloading and unacceptable voltage should be increased, a simulation of a new suggested configuration for each hour over a whole year is necessary. However, it should be mentioned that there will still be uncertainties, since load profiles are never 100% accurate.

As it has been shown, several factors may have an influence to the increased load in the network in the future, which leads to increased losses, increased amount of fault etc. Thus, this also shows a future need of optimization algorithms in relation to reduce losses, improve utilization of networks, maintaining reliability indices etc.

3.2.4 Facility with limitations

This represents a more practical challenge associated with configuring a distribution network. Limitation is in this case a broad sense, while it is not only related to a limitation in terms of maximum current (technical limits) etc.

The other part of the limitations (besides technical limitation) is related to the placement and accessibility of the facility. By placing a tie switch in a substation, which is placed with very difficult accessibility, can potentially increase the time for customers without supply. This is not appropriate from a customer perspective, while it also implies to increase the duration time of the interruption. This leads to an increment in SAIDI, which again is not appropriate for utilities. However, this constraint may be difficult to implement in an optimization process. This is due to that it will be challenging to estimate the accessibility for each substation, which should be encountered in the optimization process.

Technical limitations of facilities are also a topic for utilities, when they have to place the tie switch. As with many other technical fields, the facilities are under development, which leads to better and more resilient facilities. Therefore, facilities for 10-20 years ago may be limited by the size of today's short-circuit currents / level in reference to the thermal limits. For safety reasons some facilities (especially the switches in the facility) are not allowed to be utilized, when searching for faults in networks. Hence, it is not optimal to place a tie switch in such facilities, since it will limit the search process - and thus delay the time before the customers can be supplied again. This will again lead to an increment in SAIDI, which is not preferable.
This technical limit can also be challenging to implement in an optimization process. However, dependent on the method behind the optimization process, it may be an option to choose whether the substations have switches or not. If this option is available, it will

contribute to take this technical limitation into account, since substations with old facilities could be set to have zero switches.

3.2.5 Short-circuit level

When distribution networks are under reconfiguration, it may be the case that the distance (measured in impedance) to the last substations from the primary station have been increased. This will affect the short-circuit level to decrease in the last substation. Although the short-circuit level is reduced, it must still be ensured that the network is optimal protected. This applies particularly to the minimum short circuit level which can occur.

In general, radial network configuration often utilizes over-current relays, which often have an characteristic as shown in Figure 3.10. Typically, the characteristic includes an inverse characteristic together with a constant (instantaneous) characteristic. When setting the relay characteristic, it has to be ensured that the lowest possible short-circuit current is measurable. Hence, the lowest short-circuit current has be larger than $I>$. Practically, this setting distinguishes between load and fault currents, since it has to be ensured that the highest possible load current not exceeds $I>$. This will lead to unchallenged interruptions, which affects SAIDI and SAIFI. As also observed in Figure 3.10, the characteristic appears to be constant at higher currents. The point of intersection is given by $I>>$, and also known as the instantaneous tripping value.

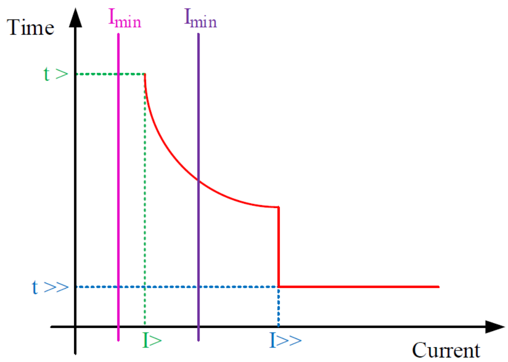

Figure 3.10: Overcurrent relay characteristic

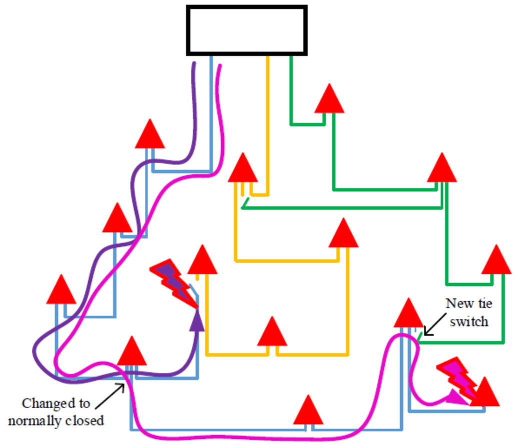

Figure 3.11: Illustration of reduced short-circuit level after reconfiguration

The tripping value $I>$ can be challenged by the reduced short-circuit level. Hence, if the reconfiguration of the network reduces the short-circuit level, it will approach the tripping value $I>$. This is illustrated by Figure 3.11, where the network from Figure 3.1 has been reconfigured. The **purple short-circuit** is the lowest possible short-circuit level *before* reconfiguration, while the **pink short-circuit** represents the *new* lowest possible short-circuit level. Due to increased impedance to the short-circuit point in the new reconfiguration, it leads to a reduced short-circuit level. Graphically, the difference between the old and new minimum short-circuit level have been included in the relay characteristic. As it can be observed in the relay characteristic, the new reconfiguration results in a unprotected network, since the minimum short-circuit level is no longer measurable by the over-current relay. Thus, it will be seen as a high load instead of a fault. These situations are not preferable and should be avoided, since it can lead to burning installations etc.

Although this appears to be a potential problem, there are two reasons why this might not be a problem:

1. Considerations regarding the reserve supply (n-1) are typically included, when overcurrent relay settings are developed.

2. The short-circuit level must not affect the optimization process, and thereby be considered as an optimization parameter.

As the first point indicates, it is custom to take into account the worst possible reserve supply situation, when the relay settings are developed. If it is taken into account, it ensures the network to be protected in normal operation mode, as well as in unusual conditions due to faults. This means that the reconfiguration process does not necessarily take the short-circuit level into account, if it is reflected in the relay settings. However, if the philosophy behind the development of relay setting are different, it might be that the short-circuit level has to be included in the optimization process in some way.

The second point is more a requirement for distribution networks in general. If it is the case that the short-circuit level is not measurable, it might be that other investments have to be done in the network to prevent against low short-circuit levels. This can be done by minimizing cable impedances, by selecting cables with larger squares etc. Hence, cases where the short-circuit level stops the optimization of reliability indices, losses etc. should not exist. Even though this results in further investments to increase the short-circuit level, it might be the case that the investments pays for itself over a few years by optimizing losses etc.

Additionally, by increasing the minimum short-circuit level will also implies to increase the maximum short-circuit level. However, this is not a problem since today's facilities have thermal limits that can handle these short-circuit levels.
Through the report it is assumed that n-1 is included in the relay settings, while this potential problem is not further considered in the optimization process later in the report.

4 | Loss Optimization Algorithm

This chapter covers the algorithm, which has been developed in order to perform a reconfiguration of a distribution network. For this purpose a common used IEEE 33-bus network as well as a smaller network from Radius[1] have been the basis for the reconfiguration. In both cases the objective is to reduce losses for a given time stamp.

In the start of the chapter the optimization algorithm, Differential Evolution (DE), will be shortly described. Secondly, the objective function behind reconfiguration with focus on reducing losses will be explained. In the same context, the subjected constraints to the objective function will be outlined. Finally, the algorithm will be applied on the two given networks.

4.1 Differential Evolution

Differential Evolution (DE) is grouped as one out of many evolutionary algorithms, which advantageously can be used for optimization problems, which includes non-linear and non-differentiable functions. Generally, DE contains the four basic steps which evolutionary algorithms are known for:

1. *Initialization:*
   This step creates an arbitrary random population with a dimension of D individuals for each candidate N. The randomly initialization process is obtained by:

   $$x_{ij} = x_{ij}^{Low} + rand(x_{ij}^{Upper} - x_{ij}^{Low}) \quad i = 1, 2, ..., D \quad j = 1, 2, ..., N \tag{4.1}$$

   Where *Low* and *Upper* denotes the lower and upper limit for each individual in the candidate. Moreover, *rand()* indicates a random number in the range of [0;1], which is multiplied on the difference between the upper- and lower limit.

2. *Mutation:*
   The mutation process exists to find new candidates in the search space, which gradually approximates the global minimum. This search process in the space is done by equation (4.2).

   $$v_{ij,G+1} = x_{r1,G} + F \cdot (x_{r2,G} - x_{r3,G}) \tag{4.2}$$

   Where x_{r1}, x_{r2} and x_{r3} represents random integers in the range [1;N]. Hence, a new individual is created by combining randomly three other individuals from the whole population. Furthermore, F denotes a mutation factor, which generally is set in the range [0;2], while G denotes the number of iteration with reference to the initial population.

[1]DONG Energy electricity distribution has changed its name to Radius per. 1 April 2016

3. *Crossover:*
   By having executed the mutation process, two different populations exists: *G* and *G+1*. To increase the diversity in the population, these two populations are combined by a crossover operation, which gives a child population u.

$$u_{ij,G+1} = \begin{cases} x_{ij,G} & if\ rand() > CR \quad or \quad j \neq randi() \\ v_{ij,G+1} & if\ rand() \leq CR \quad or \quad j = randi() \end{cases} \tag{4.3}$$

   Where CR represents a crossover constant, which typically is in the range [0;1]. Additionally, *rand()* denotes a random number in the range [0;1]. Moreover, *randi()* is implemented as a random index (integer), which is in the range [1;D]. This ensures that at least one of the individuals are changed in the child candidate $u_{ij,G+1}$.

4. *Selection:*
   This process evaluates whether the child candidate should replace the parent candidate or not. This is done by evaluating the objective function. If the objective function decreases by the child candidate compared to the parent candidate, the parent candidate is replaced by the child candidate.

$$\mathbf{x}_{i,G+1} = \begin{cases} \mathbf{u}_{i,G} & if\ f(\mathbf{x}_{i,G}) > f(\mathbf{u}_{i,G}) \\ \mathbf{x}_{i,G} & Otherweise \end{cases} \tag{4.4}$$

   Please notice that $\mathbf{x}_{i,G+1}$, $\mathbf{u}_{i,G}$ and $\mathbf{x}_{i,G}$ represents the candidate, which is a vector with D individuals.

The algorithm generally runs for a certain number of iterations. To obtain convergence, all candidates much be equal to each other. Furthermore, it is important to restart the algorithm with the same number of iterations, in order to investigate how consistent the results are. This contributes to ensure that a true global minimum has been found. Further informations and fundamental analysis regarding the differential evolution algorithm can be found in [6].

In accordance to the new proposed configurations obtained later in the report, the algorithm has been restarted 10 times to ensure a stable result. Therefore, the represented results indicates global minimums. Furthermore, the mutation factor has been set to 0.5, while the crossover constant has been set to 0.3 through the report.

4.2 The Objective Function

This report propose an algorithm to reduce losses in distribution networks by finding the optimal placement for the tie switches. The objective function of this particular problem is given by:

$$min\ f = \sum_{i=1}^{n_b} r_i \cdot |I_i|^2 \cdot k_i \tag{4.5}$$

Where n_b denotes the number of branches in the network, while r_i and I_i represents the resistance and flowing current for line i. Moreover, k_i is a binary variable (0 or 1), which represents the status of the line. Lines in service have status of 1, while out of service is denoted by 0.

Additionally, constraints must be subjected to the objective function, in order to ensure against unacceptable voltages and overloaded equipments. Moreover, it is also important to include that the new reconfigured network must have a radial structure, while the process must not propose a network with island structure. The theory of keeping radial structure is further elaborated later in the report. The voltage limitation as well as the branch power constraints are given by:

- **Voltage limitation:**
  In general, the voltage level limitation can be described by the following inequality:

$$V_{i,min} \leq V_i \leq V_{i,max} \tag{4.6}$$

Where V_i represents the actual voltage of bus i, while $V_{i,max}$ and $V_{i,min}$ represents the upper and lower voltage limit, respectively.

When including the inequality in the algorithm, it is added as a new term in the objective function given in equation (4.5). The new term is given in equation (4.7).

$$Voltage\ term = \omega_v \sum_{i=1}^{n} (V_{i,pu} - 1)^2 \tag{4.7}$$

Where n defines the total number of busses in the network, while $V_{i,pu}$ represents the actual voltage in per unit at bus i. Moreover, ω_v is a penalty factor, which can be chosen arbitrarily.

As it can be observed in equation (4.7), the actual voltage is subtracted from 1 pu. If there is a difference, the voltage term will be different from zero. If differences occurs (due to exceeded voltage limits) the voltage term must lead to a relatively high value, which is added to the objective function. The size of the voltage term is regulated by the penalty factor, which through this report has been chosen to be: $\omega_v = 1000$. Thus, by utilizing the voltage term given in equation (4.7), the algorithm tries to find a new network configuration, in which both reduces the losses and forces the voltage at the busses to be as close as possible to 1 pu.

Nevertheless, by forcing the algorithm to find a solution, in which both reduce losses and optimize the voltages to be as close as possible to 1 pu, is a compromise between cost savings and operational conditions. If network areas without generation are considered, the voltage in the network will always be less than the voltage at the primary station. In these cases, an optimization of both losses and voltage level will not lead to a configuration, which maximize cost savings due to loss reductions. Since the voltage will be improved as well, the amount of loss reduction will be reduced. This should be compared to if the objective function only include loss reduction. Generally, utility companies have some requirements for the minimum voltage level in normal conditions. Basically, they might not consider investments if the network complies with these requirements. Hence, they will likely prefer a further reduction in losses instead of both reduce losses and increase the voltage, if the voltages are acceptable. Therefore, the voltage term can be modified in a way that only penalizes the voltages, if they exceeds a certain voltage level.

$$Voltage\ term = \begin{cases} \omega_v \sum_{i=1}^{n} (V_{i,pu} - 1)^2 & if\ V_{i,pu} < 0.96pu \\ \omega_v \sum_{i=1}^{n} (V_{i,pu} - 1)^2 & if\ V_{i,pu} > 1pu \\ 0 & Otherweise \end{cases} \tag{4.8}$$

As it can be seen in equation (4.8), the voltage at bus i is only penalized if the voltage is either below a certain value (in this case 0.96 pu is chosen) or if the voltage is above 1 pu.

It should be noticed that if generation exists in the distribution network, over voltages may occur. To ensure against over voltages, the voltage term is set to always penalize the voltage if the voltages exceeds 1 pu. There are no incentives for utilities to have voltage levels that are far above the voltage of the primary station. This will simply challenge the utilities to provide a supply voltage to the customers, which is within the requirements.

- **Branch power constraint:**
  It is not suitable to purpose new network configurations, which leads to overloaded equipments. As already explained, this may contribute to an increased number of faults, while the lifetime of the equipments will be reduced as well. The overall branch power constraint are given by the following inequality:

  $$S_j \leq S_{j,max} \tag{4.9}$$

  Please note that both S_j and $S_{j,max}$ represents the magnitude of the apparent power for line j.

  A given solution obtained by the optimization process, is only feasible if none of the equipments are overloaded. This is ensured by adding a current term in the objective function, which is given in equation (4.10):

  $$Current\ term = \begin{cases} \omega_I \cdot \sum_{i=1}^{n_b} |I_{i,rated,pu} - I_{i,pu}| & if\ I_{i,rated,pu} < I_{i,pu} \\ 0 & Otherweise \end{cases} \tag{4.10}$$

  Where n_b represents the number of branches, while ω_I denotes the penalty factor. If none of the lines are overloaded the current term will equal zero, while if the line limits are exceeded, the term will be different from zero. In principle, the current term acts in the same way to the objective function, as it is the case with the voltage term. The current penalty factor is through the report chosen to be: $\omega_I = 1000$.

Based on the introduced penalization terms, the final objective function can be observed in equation (4.11).

$$min\ f = \sum_{i=1}^{n_b} r_i \cdot |I_i|^2 \cdot k_i + \sum_{i=1}^{n} (V_{i,pu} - 1)^2 + \sum_{i=1}^{n_b} |I_{i,rated,pu} - I_{i,pu}| \tag{4.11}$$

The objective function represented in equation (4.11) will be the basis for the optimization process, while it is used in the DE algorithm.

4.2.1 Encoding strategy for radial structure

Besides the voltage - and branch flow constraints, it is important that the solution obtained from the objective function is feasible. In this sense feasible solutions propose a network configuration, where radial structure exists. It should not be the case that only a part of the network has radial structure, and a other part has island structure.

In this report the radial structure is kept through the optimization process by applying an *cycle encoding strategy*, which is widely used within this area. This encoding strategy utilize loops, which are created by closing all switches in a given network. This kind of loops are also utilized by for example *Kirchhoffs Voltage Law* (KVL). In order to understand the cycle encoding strategy, consider the IEEE 33-bus network in Figure 4.1.

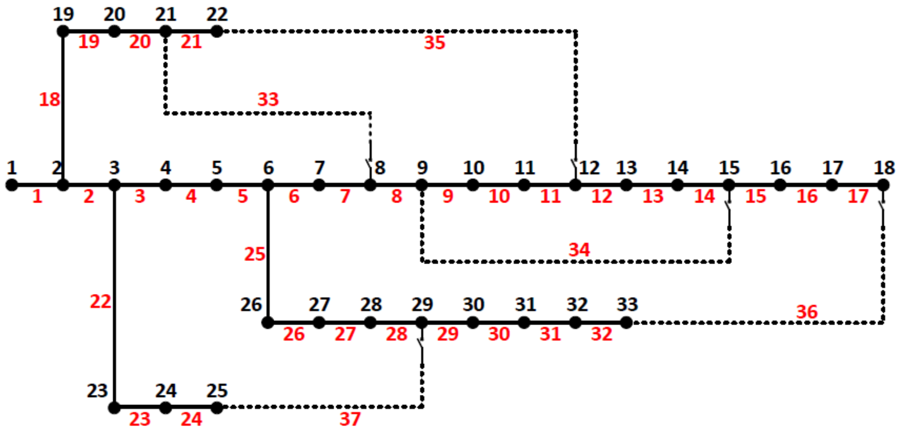

Figure 4.1: Overview of the IEEE 33-bus network

In Figure 4.1 the black dots indicates nodes in the network, where the node index is given by the black numbers. In addition, the numbering of the lines are given by the red numbers. Furthermore, it can be observed that five tie switches exists in the network, in which takes five lines out of service. These lines are represented as dotted lines (line 33, 34, 35, 36 and 37). In addition, the slack bus is set to be node 1. The aim of the reconfiguration process is to analyze, whether these five tie switches are right located in order to obtain minimum losses in the network. The loads at each node and the technical specifications for the lines, are given in Appendix B.

By applying the cycle encoding strategy for the network given in Figure 4.1, the following applies:

1. Close all tie switches in the network.
2. The number of created loops should equal to the number of tie switches.

By applying the aforementioned procedure, the loop creation in the IEEE 33-bus network can be observed in Figure 4.2.

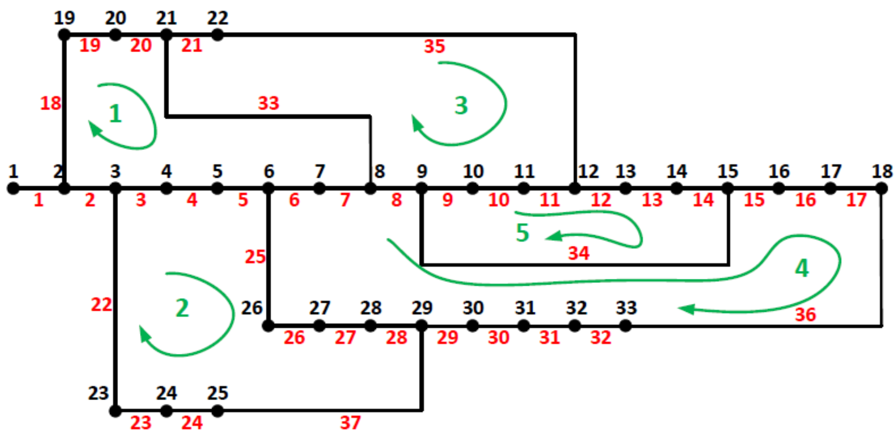

Figure 4.2: Overview of the IEEE 33-bus network with loops created by the cycle encoding strategy

Each loop will be encoded by the lines, in which the loop includes. However, the lines cannot exist in two loops, since the strategy is the following; *for each loop one of the lines should be taken out of service*. This equals to that one line from each loop should be out of service to ensure radial structure. The tie switch, which has to be opened, exists in one of the ends of the specific line that are going to be out of service. By this philosophy it is guaranteed that radial structure is kept through the optimization process.

In reference to the implementation of this encoding strategy, the lines in each loop will be encoded by a natural number, which is used for the individuals in each candidate in the DE algorithm. Hence, the number of individuals in each candidate equals to the number of loops. The loops exists as a vector with the lines as elements. By inspecting the network in Figure 4.2, the five loops includes the lines given in Table 4.1.

Loop 1	*Lines*	2	3	4	5	6	7	8	18	19	20	33
	Natural number	1	2	3	4	5	6	7	8	9	10	11
Loop 2	*Lines*	22	23	24	25	26	27	28	37			
	Natural number	1	2	3	4	5	6	7	8			
Loop 3	*Lines*	8	9	10	11	21	35					
	Natural number	1	2	3	4	5	6					
Loop 4	*Lines*	15	16	17	29	30	31	32	36			
	Natural number	1	2	3	4	5	6	7	8			
Loop 5	*Lines*	12	13	14	34							
	Natural number	1	2	3	4							

Table 4.1: Overview of lines included in each created loop

As it can be observed in Table 4.1, each line is only included in one of the loops. The allocation process of lines, which can exist in two loops, have been done randomly. In addition, by increasing the network, this cycle encoding strategy become very complex, however this strategy still significantly reduces the search space compared to binary coding [7]. Strategies for how lines, which can exist in several loops, are assigned to a specific loop, will not be further considered and developed in this report.

4.3 Applying the Algorithm

As already mentioned, the number of individuals in each loop equals the number of loops. When the DE algorithm has found a new child candidate, in which should be compared to the parent candidate, the selection process is done by a load flow calculation. The candidate with the minimum total losses are selected. The load flow calculations are done by the Newton-Raphson method, where MATPOWER in Matlab have been utilized for this purpose.

The algorithm have been applied for the IEEE 33-bus network, which is already shown in Figure 4.1 and Figure 4.2. Furthermore, the algorithm have been applied on a limited network area from Radius, which contains four feeders. This should be compared to the 33-bus network, which only contain one feeder. The networks will be analyzed individually in the coming sections.

4.3.1 IEEE 33-bus network

By using the loops as stated in Table 4.2, it is possible to obtain the optimal configuration with respect to reduced losses. Since the load is generally high in the network (no generation exists), it is not possible to reconfigure the network in a way that ensures a minimum voltage of 0.96 pu ($U_n = 12.66kV$). However, a new configuration has been found with two different objectives. The first is only considering losses, while the second is both considering losses, and maximizing the voltages to be as close as possible to 1 pu. The results can be observed in Table 4.2.

Objective		***Before reconfiguration***	***After reconfiguration***
Only reduce losses	*Tie switches*	33, 34, 35, 36, 37	7, 9, 14, 32, 37
	Power loss	202.683 kW	139.554 kW
	Power loss reduction	-	31.1465 %
	Minimum voltage	11.559 kV	11.873 kV
Reduce losses and maximize voltages	*Tie switches*	33, 34, 35, 36, 37	7, 9, 14, 28, 32
	Power loss	202.683 kW	139.981 kW
	Power loss reduction	-	30.9359 %
	Minimum voltage	11.559 kV	11.897 kV

Table 4.2: Overview of results for IEEE 33-bus network

As it can be observed in Table 4.2, it is a comprises of how large the reduction in losses should be. If the objective only consider loss reduction, it leads to a total reduction of 31.14 %. However, if the objective in the same time includes maximization of the voltages in the network to be as close as possible to 1 pu, it is lowering the total reduction of losses to 30.93 %. In addition, it increases the minimum voltage by only 24 V with respect to the objective of only reduce losses. This is a relatively small improvement, while it will not be more sufficient to have a 24 V higher minimum voltage, compared to obtain a bit higher loss reduction. Hence, in this case the comprise of lowering the reduction of losses by increasing the voltage, will not be preferred. This might not be the case in all networks, where the reduction in total losses due to the objective of increasing the minimum voltage, may be preferred in other situations. Nonetheless, the two different objectives will lead to voltages at each node in the entire network, which will differs from each other. The voltage profiles for each case can be seen in Figure 4.3 and Figure 4.4.

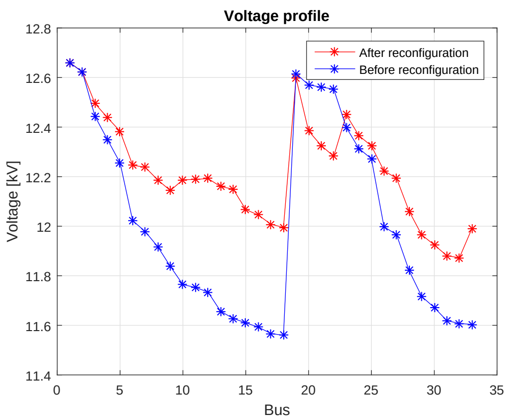

Figure 4.3: Voltages in the network. Objective: Only reduce losses.

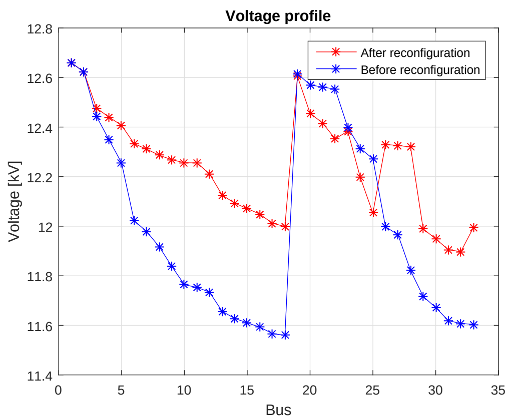

Figure 4.4: Voltages in the network. Objective: Reduce losses and maximize minimum voltage level.

The voltages in the network are obviously dependent on the objective for the optimization. By investigating the voltage after reconfiguration, the voltage level is generally, as expected, at a higher level in the case, where the objective includes maximization of the minimum voltage. In addition, the represented results in Figure 4.3 and Figure 4.4 are obtained each time the algorithm is restarted. How the convergence develops in the DE algorithm, can be investigated in Figure 4.5.

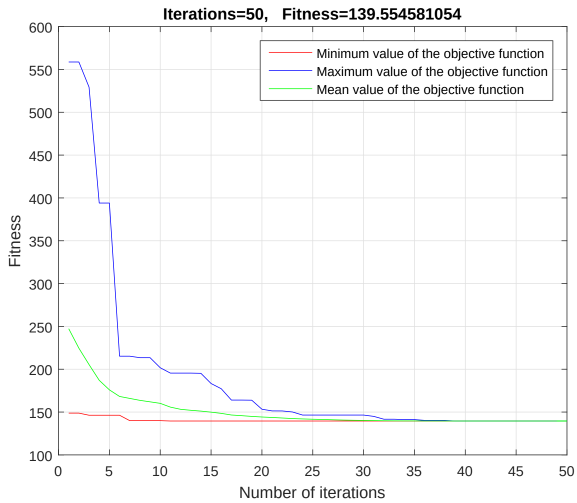

Figure 4.5: Overview of how the fitness develops for each iteration, when the objective is only to reduce losses.

As it can be observed in Figure 4.5, convergence is obtained with around 40 iterations. By running the algorithm several times with the same option chosen, the same convergence picture has been observed - which indicates a true global minimum.
Nevertheless, it can be observed in both Figure 4.3 and Figure 4.4 that the voltage level is generally increased in the entire network. This is one of the other benefits of configuring networks in the most reliable way. This may postpone some investments, since it in the new configuration with higher voltage, may be easier to resupply customers after a fault has occurred. This can in the end save time, which directly can be related to SAIDI. Hence, by reconfigure networks in the most reliable way, the voltage will in general be increased, which contributes to keep the the reliability indices at a certain level.

By choosing the objective of only reduce losses, the new proposed network configuration can be experienced in Figure 4.6.

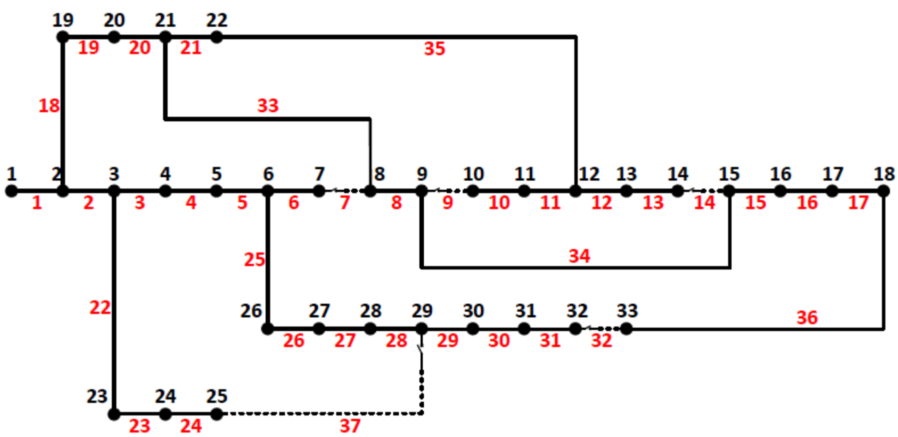

Figure 4.6: The proposed new configuration for the 33-bus network with an objective of only reduce losses.

As it can be seen in Figure 4.6, the new proposed configuration is keeping the radial structure, which was the aim of introducing the cycle encoding strategy. Thus, the new tie switches in reference to reduce losses are now indicated by the dotted lines in Figure 4.6.

4.3.2 A limited network area from Radius

The limited network from Radius contains four feeders from the same primary station, which is shown in Figure 4.7. The nominal voltage in the network is 10 kV, however the voltage at the primary station is automatically regulated to be 10.4 kV. This voltage is used as the reference voltage in the slack bus in MATPOWER.

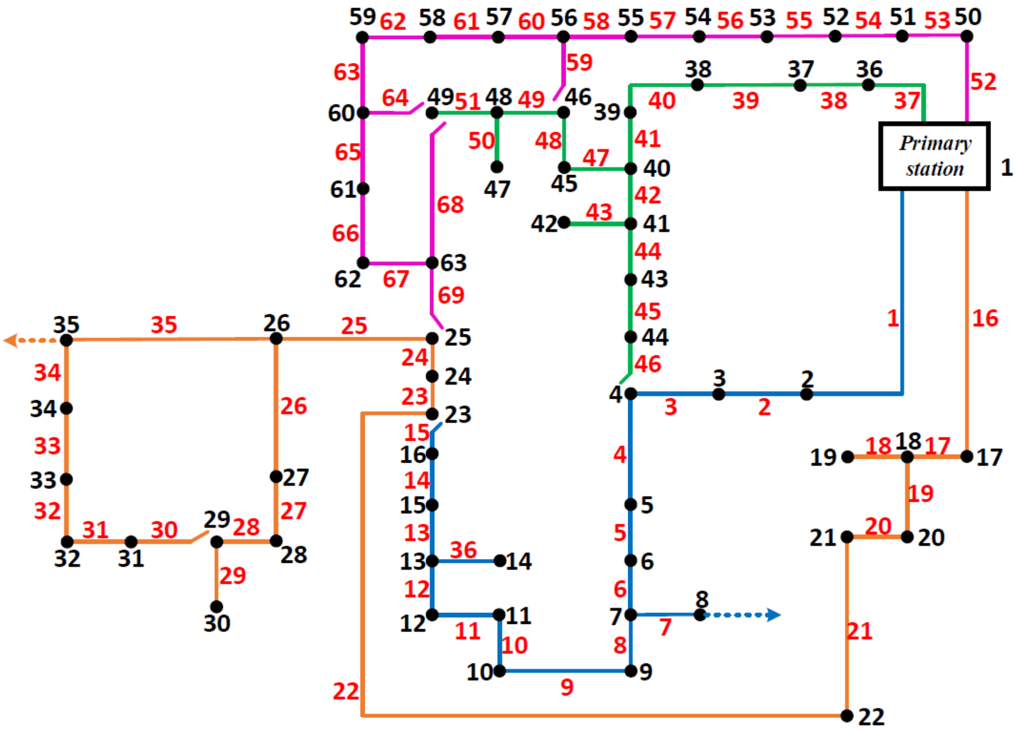

Figure 4.7: Overview of the limited network from Radius. The node index is given by the black numbers, while the line index is given by the red numbers.

The limitation of the network can be observed by the two dotted lines, which is blue and orange, respectively. It is in this case assumed that the already existing tie switch at these two locations are the optimal ones. The technical data for the network can be found in Appendix C, where the used loads represents maximum loads.

It might be observed how the complexity of the network have increased compared to the IEEE 33-bus network. This is especially observed when the loops have to be created. By closing all existing tie switches, the created loops can be experienced in Figure 4.8.

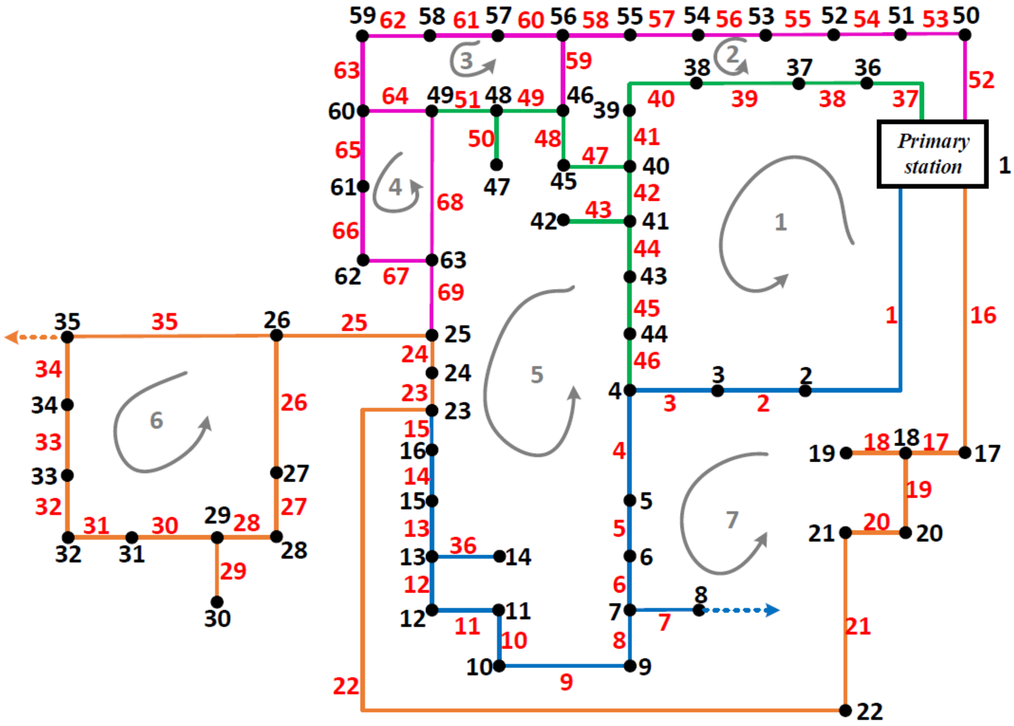

Figure 4.8: Overview of the limited network from Radius with loops created.

It can be observed that seven loops are created by closing all tie switches, which equals to the initial number of tie switches in the network. The next step is to assign each line to a specific loop. This can be observed in Table 4.3.

Loop 1	*Lines*	1	2	3	37	38	39	40	41	42	44	45	46					
	Natural number	1	2	3	4	5	6	7	8	9	10	11	12					
Loop 2	*Lines*	47	48	52	53	54	55	56	57	58	59							
	Natural number	1	2	3	4	5	6	7	8	9	10							
Loop 3	*Lines*	49	51	60	61	62	63	64										
	Natural number	1	2	3	4	5	6	7										
Loop 4	*Lines*	65	66	67	68													
	Natural number	1	2	3	4													
Loop 5	*Lines*	23	24	69														
	Natural number	1	2	3														
Loop 6	*Lines*	26	27	28	30	31	32	33	34	35								
	Natural number	1	2	3	4	5	6	7	8	9								
Loop 7	*Lines*	4	5	6	8	9	10	11	12	13	14	15	16	17	19	20	21	22
	Natural number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17

Table 4.3: Overview of the lines assigned to each loop created in the limited network from Radius

It should be noticed that lines which supplies satellite substations such as line 18, 29, 36, 43 and 50 are not included in any loops, since the switch in these substations always have to be closed in order to supply the customers. In addition, line 25 is not included in any loops, while the switches around line 25 will always be closed. This makes sense due to the fact that if there was a possibility of disconnecting line 25, all the customers in loop 6 will lose the supply.

Results

Based on the created loops, the algorithm have been applied to the system. The initial configuration of the network is given by Figure 4.7, which is the actual configuration of the network. The optimization results can be seen in Table 4.4.

Objective		***Before reconfiguration***	***After reconfiguration***
Only reduce losses	*Tie switches*	15, 30, 46, 59, 64, 68, 69	10, 30, 45, 59, 64, 67, 69
	Power loss	144.4001 kW	120.4671 kW
	Power loss reduction	-	16.5741 %
	Minimum voltage	10.1489 kV	10.2137 kV
Reduce losses and maximize minimum voltage level	*Tie switches*	15, 30, 46, 59, 64, 68, 69	11, 30, 46, 59, 64, 67, 69
	Power loss	144.4001 kW	120.6609 kW
	Power loss reduction	-	16.4399 %
	Minimum voltage	10.1489 kV	10.2299 kV

Table 4.4: Overview of results for Radius network

As it can be observed in Table 4.4, the minimum voltage before reconfiguration is above 0.96. By Table 4.4 it is observed that the network losses is reduced by around 16.5 %. A higher reduction in network losses is obtained, if the objective is only to reduce losses (the voltage levels are not penalized, since they not exceeds the upper- and lower limits). The improvements in voltage levels by also maximize the minimum voltage (by using the voltage term given in equation (4.7)) is not excessive, while the best objective in this case might be to only minimize losses.

The voltage profile in both cases are available in Figure 4.9 and Figure 4.10.

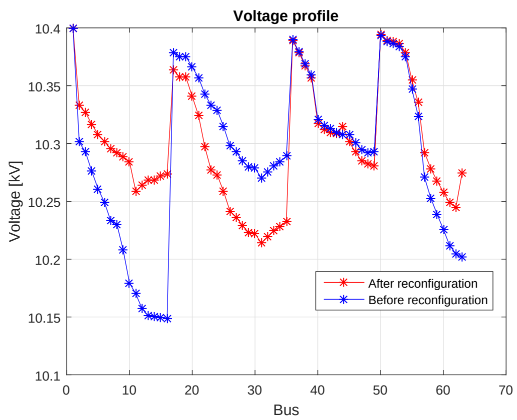

Figure 4.9: Voltages in the network. Objective: Only reduce losses.

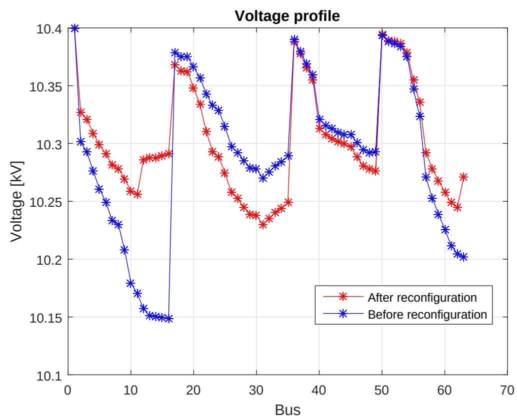

Figure 4.10: Voltages in the network. Objective: Reduce losses and maximize minimum voltage level.

As shown by the results in Table 4.4, the differences between the two cases are not large. The same applies for the voltage profiles, which is very similar to each other. It can be observed in both cases that the voltage at node 17 to node 35 have generally a lower voltage after the reconfiguration. These nodes equals to the nodes which are supplied by the orange feeder. By considering the new proposed network configuration, this reduction in voltage for the nodes at the orange feeder make sense, since this feeder have been allocated new loads.

The new network configuration by considering the objective of only reducing losses, can be seen in Figure 4.11.

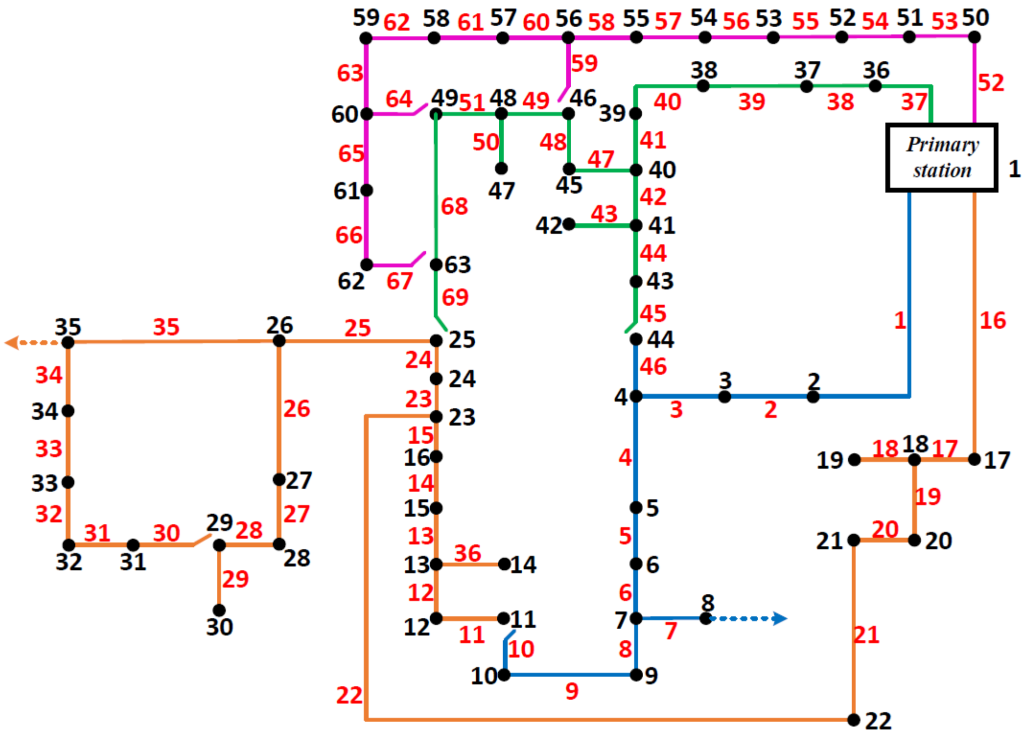

Figure 4.11: Overview of the limited network from Radius with new network configuration

As it is observed by Figure 4.11, the orange feeder has been assigned the largest amount of new loads, while the green feeder has only been assigned one new load (node 63). Hence, since the reconfiguration process not changes all tie switch locations in reference to the initial configuration, the initial location (and thereby the actual daily operation of the network) can be concluded to be close to optimal. This conclusion is only based on the assumption of considering the represented four feeders, and not the neighbouring feeders. Furthermore, this optimal tie switch locations are based on maximum loads, while another configurations (and thereby a further total loss reduction over a year) may be obtained by consider other time stamps.

Changed Load in the Network

Compared to the already examined optimization cases in both the IEEE 33-bus network and the network from Radius, none of the lines have experienced overload in the initial configuration. Even though some child candidates through the optimization process may lead to overloaded lines, it is not experienced due to the current term implemented in the objective function given in equation (4.11). In order to investigate whether the current term forces the proposed configuration to avoid overloaded lines, it is decided to add two new loads in the Radius network.

By considering the initial configuration given in Figure 4.7, and connecting a new load at both node 57 and 61 (each load is 1 MW), line 58 is observed to have a loading of 106.95 %. This is not allowed, while it is now known that the optimization process needs to find a new configuration to avoid overloading.

The results by running the DE algorithm can be observed in Table 4.5. As expected the total losses in the initial network has increased due to the implementation of 2 MW in the network. This automatically leads to a lower minimum voltage, which is also experienced in the results.

Objective		*Before reconfiguration*	*After reconfiguration*
Reduce losses and maximize minimum voltage level	*Tie switches*	15, 30, 46, 59, 64, 68, 69	10, 31, 44, 59, 63, 66, 69
	Power loss	232.4346 kW	178.9368 kW
	Power loss reduction	-	23.0163 %
	Minimum voltage	10.0391 kV	10.1769 kV

Table 4.5: Overview of results for Radius network with new loads

Furthermore, it is also observed that the proposed new configuration in Table 4.5 is different from the proposed configuration given in Table 4.4. By investigating the new minimum voltage level by performing the proposed configuration, it is improved by over 100 V. This is a significantly improvement, which indicates that the initial network configuration was not optimal after having two new loads connected in the network. The voltage profile in the network can be observed in Figure 4.12.

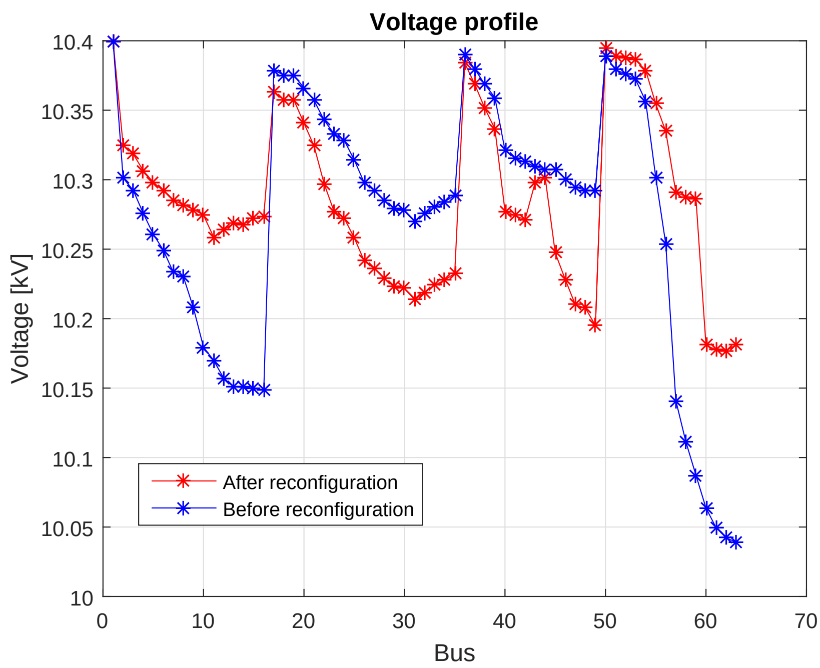

Figure 4.12: Voltage profiles by reconfiguration the network with new loads

As it can be seen in Figure 4.12, the voltage at node 50 to 63 have been significantly improved. These nodes represents the pink feeder, while it indicates that one of the loads have been shifted to one of the other feeders. The new proposed network configuration after having connected two new loads can be seen in Figure 4.13.

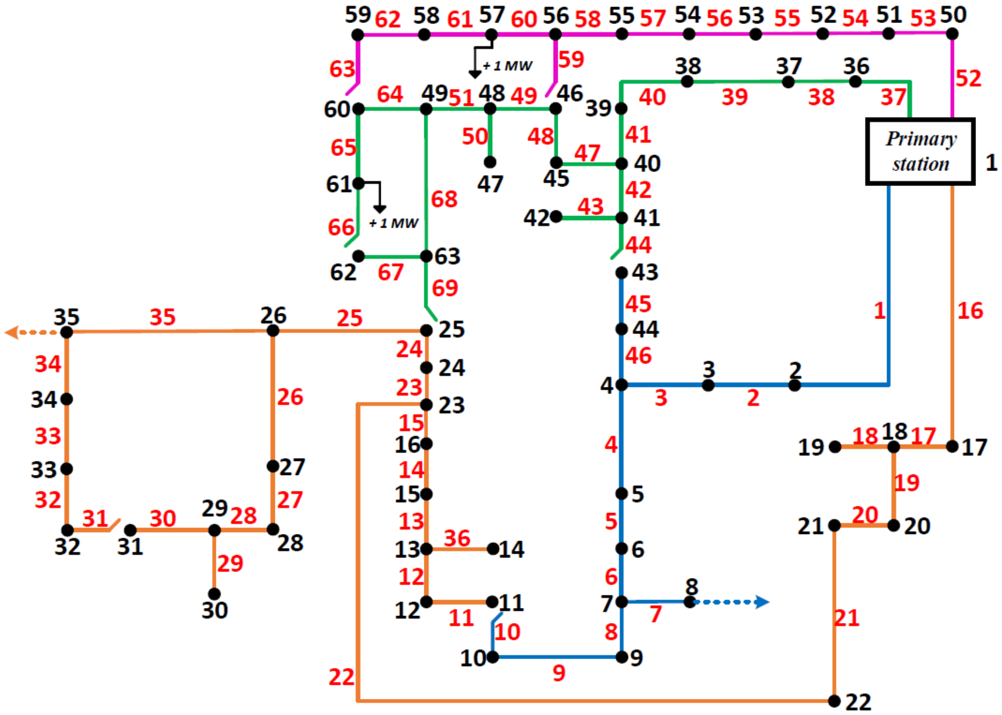

Figure 4.13: Overview of the new proposed network configuration after having connected two new loads

As it can be observed in Figure 4.13, the network has been reconfigured in such a way that leads the green feeder to supply one of the two new loads. Hence, it can be concluded that the current term in the objective function seems to avoid overloaded lines as expected. Furthermore, this example shows that reconfiguration of networks, which optimizes in accordance to reduce losses, and maximizing the voltage to be as close as possible to 1 pu, can be used as an effective planning tool for grid planners. This ensures that the optimal operational conditions are found in each scenario that the grid planner evaluates.

Implementation of Generation in the Network

The network from Radius has once again been modified, where a total generation of 2 MW has been implemented (the new loads are removed). It is assumed that the generation is divided into two generators, where both generators produces 1 MW. One of the generators are located at node 34, while the second generator is located at node 31.

In this case it is expected to observe voltages that exceeds 1 pu. This will in accordance to the voltage term given in equation (4.8) be penalized. Thus, it is expected that the maximum voltage in the network will be minimized to be as close as possible to 1 pu. Therefore, the objective utilized in this optimization is to both reduce losses, and force the voltage to be as close as possible to 1 pu, if the voltage either exceeds 0.96 pu or 1 pu.

The results by running the DE algorithm can be observed in Table 4.6. As it can be observed, the total losses in the initial configuration (given in Figure 4.7) has decreased, which is due to the increased voltage in the network. Moreover, it can be observed that the maximum voltage is above 10.6 kV, which is potentially high with respect to the voltage levels in the low voltage networks. However, by optimizing the network, the losses are reduced with around 45 %, which is a significantly reduction. Moreover, it can be observed that the maximum voltage is reduced with around 150 V, which also is a significantly reduction in the voltage. This reduction might ensure that over voltages in the low voltage network not occurs. Finally, it is also observable that the minimum voltage is increased, hence the voltage profile in the entire network has in general been optimized.

Objective		***Before reconfiguration***	***After reconfiguration***
	Tie switches	15, 30, 46, 59, 64, 68, 69	10, 33, 24, 46, 48, 63, 65
Reduce losses and optimization of the voltage levels	*Power loss*	155.0225 kW	84.6737 kW
	Power loss reduction	-	45.3797 %
	Minimum voltage	10.149 kV	10.290 kV
	Maximum voltage	10.614 kV	10.462 kV

Table 4.6: Overview of results for Radius network with generation of 2 MW implemented

The voltage profile for the entire network before - and after the reconfiguration can be observed in Figure 4.14.

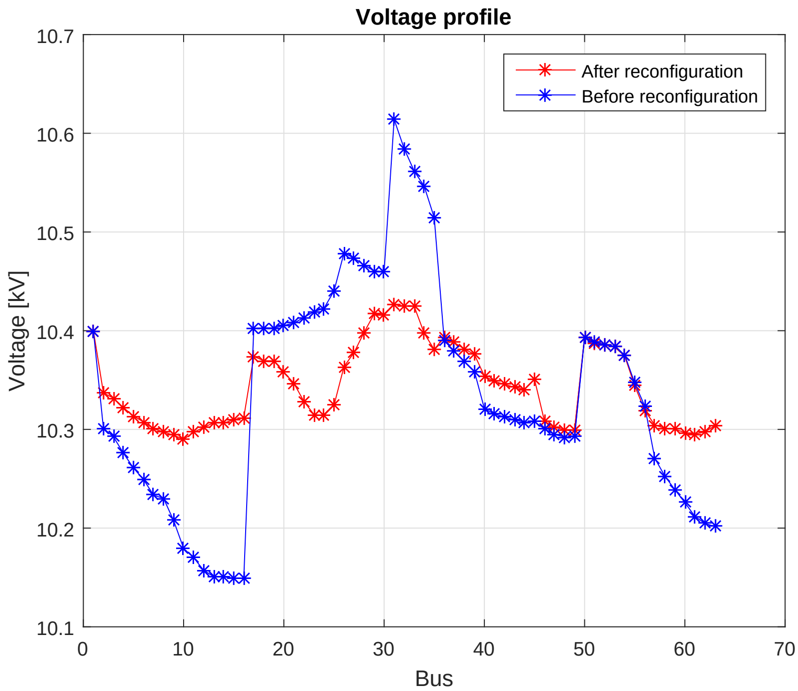

Figure 4.14: Voltage profiles by reconfiguration the network with implementation of two generators

As it can be observed in Figure 4.14, the voltage profile has been significantly optimized with respect to the initial configuration. The voltages in the entire network has become more closer to each other, while the difference between the highest and lowest voltage level is not far from each other after the reconfiguration.

As expected the voltage at node 17 to node 35 experiences a large increase in the voltage level in the initial configuration, since both generators are connected to the orange feeder. The increment in the voltage level at the orange feeder is reduced by the new proposed network configuration shown in Figure 4.15.

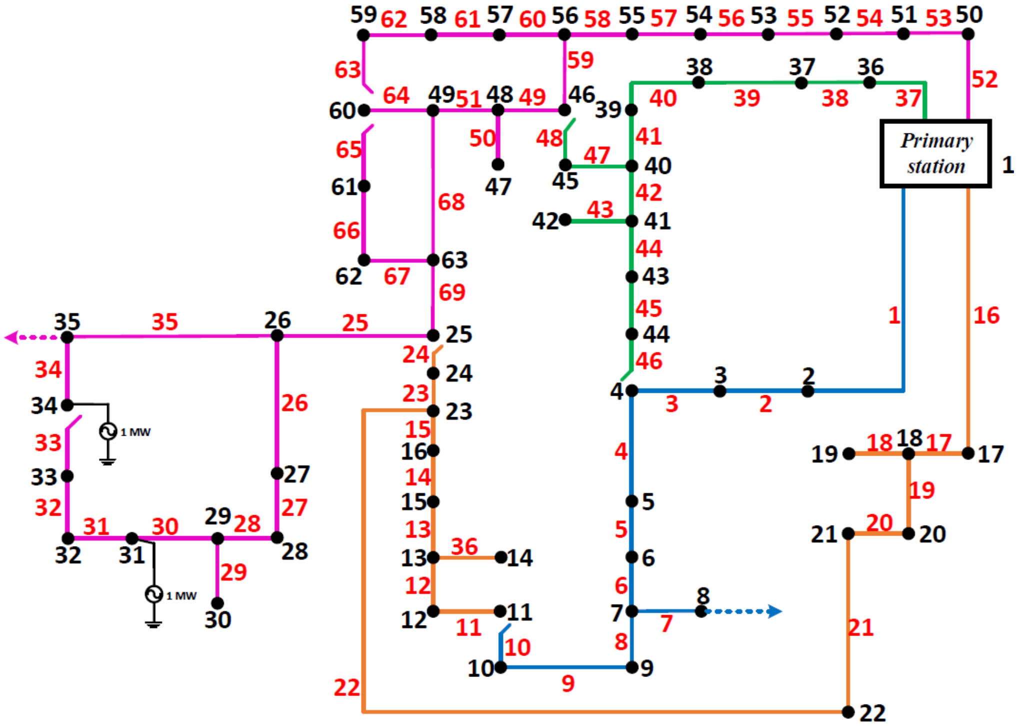

Figure 4.15: Overview of the new proposed network configuration after having implemented two generators

As it can be observed, the pink feeder has acquired the supply of node 25 to node 35 after the reconfiguration. These nodes was supplied from the orange feeder before. Moreover, it can be observed that a switch between the two generators has been established. This make sense since it obviously will decrease the voltage by dividing the generations to flow in two different directions.

As for the case with implementation of new loads, this case also shows that optimization of networks in accordance to reduce losses and optimizing the voltage levels, is an effective planning tool for grid planners.

5 | Conclusion

This report has examined optimization of distribution networks with a radial structure. The optimization has been based on minimization of losses, as well as optimization of the voltages in the network.

Overall, it has been found that power quality of a distribution network is a composite size of *voltage quality* and *supply reliability*. The voltage quality represents the operational conditions that affects the sinusoidal voltage wave. The supply reliability represents how well the distribution network performs in terms of customer interruptions, and how long these interruptions lasts.
In general, two common reliability indices are utilized in order to describe customer interruptions. These are also known as: *System Average Interruption Frequency Index (SAIFI)* and *System Average Interruption Duration Index (SAIDI)*. SAIFI represents how many interruptions an average customer experience over a year, while SAIDI represents how many hours without supply an average customer will experience through a year. These indices are common used in both grid planning, and to benchmark utilities against each other.

Based on the reliability indices, it is possible for the utilities to monitor the development in the network, while SAIDI and SAIFI can be used in the decision-making process, if investments in the network has to be performed. However, the balance between a satisfactory reliability level and investments is a delicate balance. In this context, the reconfiguration of networks was found to be a preferable tool before performing investments. By reducing the losses it automatically improve the voltage level in the network to some extent - which refers to the voltage quality. This will improve the operational level in normal conditions, as well as the conditions when a fault occurs. Especially improvements in situations when fault occurs are quite valuable for the utilities. This is due the fact that these improvements contributes to restore the supply faster in case of a fault occurs. This indirectly implies to improve SAIDI. Hence, these improvements can potentially postpone investments for several years, which is preferable in today's power system, where uncertainties regarding future load profiles are unknown. This is mainly due to the renewable energy sources such as electric vehicles and heat pumps.

Through this report the objective has only been to reduce losses, while this objective has been possible to simply describe by ohms law. However, when performing reconfiguration of networks, several constraints needs to be taken into account. First, it is extremely important to ensure against overloaded equipments, as well as under- and over voltages. These limits was implemented as a penalization term in the objective function, which was found to work in practice. By this implementation it allows the optimization process to optimize the voltage level with respect to, for example, 1 pu.
Additionally, several other challenges regarding reconfiguration of networks was found and analyzed through the report. Depending on the construction of the network, and the daily

operation of the network, the following potentially issues was found:

- Increased voltage due to increased impedance after reconfiguration.
- Reserve supply.
- Dynamically loading profiles.
- Facilities with limitations.
- Minimizing of short-circuit level.

It was found that even though a reconfiguration process increases the impedance from the primary station to substations with generation installed, it does not lead to critical over voltages. This was analyzed by simulations in PowerFactory, while it was concluded not to be a part of the optimization process.

The reserve supply (n-1) is an important factor for utilities, since they aim to have satisfactory customers regarding the supply. When reconfigure the network, it can potentially lead to configurations, where the reserve supply not complies with the utilities requirements. However, by optimizing the network in reference to losses, might not contributes to an impairing reserve supply. This issue might not exist for all utilities, while it depends among others on the construction of the network, the utilities own requirements etc.

Due to the fact that a reconfiguration process needs to be based on a certain time stamp, estimating of loading profiles plays an important role. This report has analyzed the influence by an increasing amount of electric vehicles and heat pumps. In general, it was found that a reconfiguration process needs to optimize the operational conditions, while the process should not, as it is when planning new networks, be based on the maximum peak load observed in the network. Therefore, if areas have a larger number of heat pumps installed, it leads to an offset of the loading level. It was found that months close to March and October have demands from the heat pumps close to each other, while these months could be interesting from a reconfiguration perspective. In addition, it was difficult to estimate whether electric vehicles will contribute to new interesting time stamps from a reconfiguration perspective. However, they contributes to new peaks in the demand, which should be considered in reference to avoid overloaded equipments. Therefore, it was concluded that when a new network configuration was found, it should be simulated each hour for each day over a year, in order to secure against overloading and unacceptable voltages.

Furthermore, it is well-known that utilities have facilities that might not be able to withstand today's short-circuit level, which is due to many changes in the network since the facility was commissioned. Hence, open switches are not preferable to locate at these locations. However, it was found that this easily can be implemented in the optimization process by a binary representation.
Nonetheless, the minimum short-circuit level in the network will be affected by reconfigure the network. In some cases it will increase, and in other cases it will decrease. It was found to be critical if the minimum short-circuit level was decreasing too much, since it will approach relay settings. This can influence the relay to not trip, since it see the high currents as a load instead of a fault, which potentially can lead to burning installations. However, reserve supply (and thereby decreased short-circuit level) is typically considered when relay settings are performed, while this issue was concluded not to be problematic in reference to reconfiguration of networks.

Nevertheless, one of the most important part of the reconfiguration process it to obtain feasible solutions, which in this case relates to proposed network configurations that have radial structure. Through this report the differential evolution algorithm has been used, which is known as one of the evolutionary optimization algorithms. To keep the radial structure in the network, the population in algorithm was based on natural numbers from loops. It was found efficient to use a *cycle encoding strategy* to maintain the radial structure. By closing all switches in the network, loops will automatically be created, which can be used to ensure the radial structure. This is found as an much more sufficient way to ensure the radial structure compared to binary representations in the algorithm.

On behalf of the cycle encoding strategy, two networks was optimized with the same objective; reduce losses. The networks was a IEEE 33-bus network, and a limited network area from Radius. Due to the implementation of voltage limitation, the objective was also to force the voltages to be as close as possible to 1 pu. The algorithm was found to obtain convergence each time, while the IEEE 33-bus network was optimized with a reduction of 30 % in losses. This was found to also improve the voltages in the network, which is another important advantage by reconfiguration networks. This can contribute to maintain a certain reliability level, while investments can be postponed.
Furthermore, the network from Radius was optimized by around 16 % in losses, where the voltages was improved as well. Additionally, by using the network from Radius two other cases was investigated. One case added 2 MW in the network (2 x 1 MW at two different nodes), and the other case implemented 2 MW generation (2 x 1 MW at two different nodes). In both cases it was found that the penalizations, in terms of both the voltage and line flow limits in the objective function, acts as required. In both cases the new proposed configuration avoided under - and over voltages, as it also avoided overloaded equipments. This shows that such reconfiguration processes also can be used as an effective planning tools for grid planner, since the optimization process finds the most optimal operational conditions, where all limitations are talking into account.

By the increasing interest of utilizing the existing assets in the network, tools as reconfigurations are found to be of interest in the future. These kind of optimizations will contribute to postpone investments, which can end up as being quite valuable with a future, where uncertainties about the load pattern exists. This contributes to develop networks in the most reliable way in the future.

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A | Overview of the low voltage network

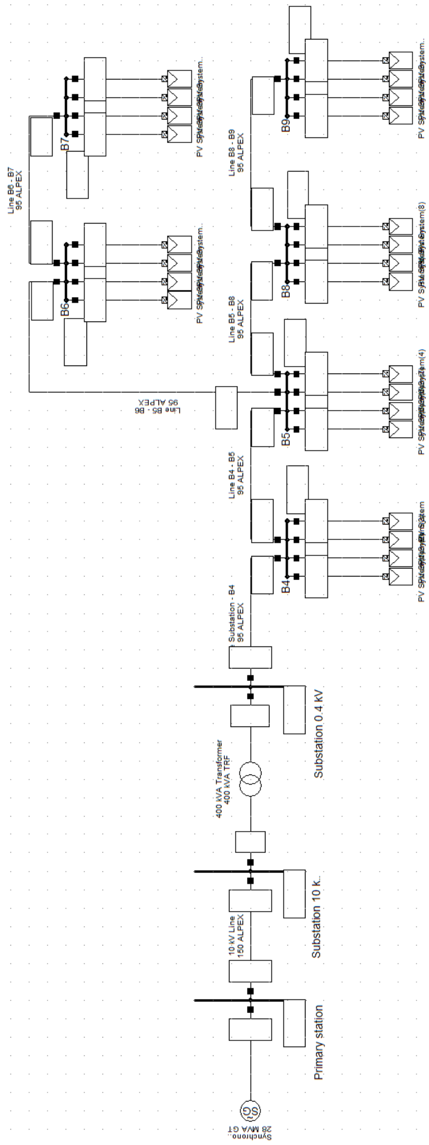

Figure A.1: Overview of the low voltage network in PowerFactory

B Technical data for IEEE 33-bus network

From node	***To node***	***R [ohm]***	***X [ohm]***	***To node active power [MW]***	***To node reactive power [MVAr]***
1	2	0.0922	0.0477	0.1000	0.0600
2	3	0.4930	0.2511	0.0900	0.0400
3	4	0.3660	0.1864	0.1200	0.0800
4	5	0.3811	0.1941	0.0600	0.0300
5	6	0.8190	0.707	0.0600	0.0200
6	7	0.1872	0.6188	0.2000	0.1000
7	8	0.7114	0.2351	0.2000	0.1000
8	9	1.0300	0.7400	0.0600	0.0200
9	10	1.0440	0.7400	0.0600	0.0200
10	11	0.1966	0.0650	0.0450	0.0300
11	12	0.3744	0.1298	0.0600	0.0350
12	13	1.4680	1.1550	0.0600	0.0350
13	14	0.5416	0.7129	0.1200	0.0800
14	15	0.5910	0.5260	0.0600	0.0100
15	16	0.7463	0.5450	0.0600	0.0200
16	17	1.2890	1.7210	0.0600	0.0200
17	18	0.7320	0.5740	0.0900	0.0400
2	19	0.1640	0.1565	0.0900	0.0400
19	20	1.5042	1.3554	0.0900	0.0400
20	21	0.4095	0.4784	0.0900	0.0400
21	22	0.7089	0.9373	0.0900	0.0400
3	23	0.4512	0.3083	0.0900	0.0500
23	24	0.8980	0.7091	0.4200	0.2000
24	25	0.8960	0.7011	0.4200	0.2000
6	26	0.2030	0.1034	0.0600	0.0250
26	27	0.2842	0.1447	0.0600	0.0250
27	28	1.0590	0.9337	0.0600	0.0200
28	29	0.8042	0.7006	0.1200	0.0700
29	30	0.5075	0.2585	0.2000	0.6000
30	31	0.9744	0.9630	0.1500	0.0700
31	32	0.3105	0.3619	0.2100	0.1000
32	33	0.3410	0.5302	0.0600	0.0400
21	8	2.0000	2.0000	-	-
9	15	2.0000	2.0000	-	-
12	22	2.0000	2.0000	-	-
18	33	0.5000	0.5000	-	-
25	29	0.5000	0.5000	-	-

Table B.1: Overview of technical data in the IEEE 33-bus network

C | Technical data for Radius network

From node	*To node*	*R [ohm]*	*X [ohm]*	*B [μS]*	*To node active power [MW]*	*To node reactive power [MVAr]*
1	2	0.3713	0.1832	361.481	0.2453	0.0349
2	3	0.0347	0.0184	42.568	0.2964	0.0423
3	4	0.0723	0.0384	88.750	0.1753	0.0249
4	5	0.0705	0.0241	44.730	0.1625	0.0231
5	6	0.0568	0.0194	36.021	0.5564	0.0793
6	7	0.0982	0.0233	34.672	0.2633	0.0375
7	8	0.1638	0.0389	57.905	0.2921	0.0416
7	9	0.2054	0.0489	72.834	0.2391	0.0341
9	10	0.2601	0.0622	92.513	0.2367	0.0337
10	11	0.1017	0.0247	36.756	0.3865	0.0551
11	12	0.1931	0.0466	69.328	0.1894	0.0269
12	13	0.1205	0.0289	42.976	0.2330	0.0332
13	15	0.0466	0.0306	51.459	0.1024	0.0146
15	16	0.0288	0.0189	31.808	0.2948	0.0420
16	23	0.0321	0.0211	35.484	0.11373	0.016206
1	17	0.16058	0.0777	148.609	0.12225	0.01742
17	18	0.028288	0.01224	15.808	0.07101	0.010118
18	19	0.040144	0.01737	22.434	0.04606	0.006563
18	20	0.079248	0.03429	44.287	0.00	0.00
20	21	0.077558	0.037544	70.163	0.17948	0.025575
21	22	0.135936	0.072216	166.752	0.19268	0.027455
22	23	0.108416	0.057596	132.886	-	-
23	24	0.054587	0.072927	26.535	0.29506	0.042044
24	25	0.216783	0.072927	129.178	0.30441	0.043376
25	26	0.379362	0.186932	423.348	0.01565	0.00223
26	27	0.313537	0.073381	104.667	0.01386	0.001975
27	28	0.44608	0.105944	157.657	0.02306	0.003286
28	29	0.392	0.0931	138.505	0.19095	0.027209
29	30	0.35424	0.084132	125.198	0.03891	0.005544
29	31	0.15648	0.037164	55.304	0.16936	0.024132
31	32	0.46304	0.109972	163.651	0.04062	0.005788
32	33	0.36992	0.087856	130.740	0.01337	0.001905
33	34	0.25376	0.060268	89.685	0.07774	0.011077
34	35	0.25376	0.060268	89.685	0.13534	0.019285
35	26	0.30784	0.073112	108.799	-	-
13	14	0.0374	0.0245	41.280	0.1506	0.0214

Table C.1: Technical data for Radius network

From node	*To node*	*R [ohm]*	*X [ohm]*	*B [μS]*	*To node active power [MW]*	*To node reactive power [MVAr]*
1	36	0.04505	0.02464	54.518	0.06805	0.009697
36	37	0.04352	0.0238	52.830	0.09458	0.013477
37	38	0.049792	0.026452	61.055	0.00	0.00
38	39	0.04224	0.02772	46.652	0.01687	0.002404
39	40	0.169472	0.111216	187.176	0.2974	0.042377
40	41	0.072064	0.047292	79.592	0.35435	0.050492
41	42	0.142272	0.048564	90.251	0.29709	0.042333
41	43	0.19168	0.045524	67.745	0.29504	0.042041
43	44	0.184628	0.038388	47.536	0.1675	0.023867
4	44	0.160332	0.035773	47.444	-	-
40	45	0.10649	0.069888	117.621	0.44519	0.063436
45	46	0.076416	0.050148	84.399	0.30797	0.043883
46	47	0.079232	0.051996	87.509	0.381	0.05429
47	48	0.131664	0.05064	78.849	0.26263	0.037423
47	49	0.08176	0.049056	81.570	0.39277	0.055967
1	50	0.032384	0.017457	39.375	0.18878	0.0269
50	51	0.032384	0.021252	35.568	0.06197	0.00883
51	52	0.009472	0.006216	10.461	0.05882	0.008381
52	53	0.013056	0.008568	14.419	0.06724	0.009581
53	54	0.051584	0.033852	56.972	0.26103	0.037195
54	55	0.192428	0.108076	182.807	0.22343	0.031837
55	56	0.18208	0.043244	64.352	0.146	0.020804
46	56	0.11904	0.028272	42.072	-	-
56	57	0.44032	0.134848	134.007	0.23729	0.033812
57	58	0.17216	0.052724	52.395	0.1505	0.021445
58	59	0.14752	0.045178	44.896	0.11566	0.016481
59	60	0.15296	0.046844	46.551	0.28148	0.040109
49	60	0.14144	0.033592	49.988	-	-
60	61	0.20832	0.063798	63.400	0.22292	0.031764
61	62	0.13952	0.042728	42.461	0.43181	0.048708
62	63	0.143284	0.034352	51.119	0.32223	0.045915
49	63	0.271953	0.061171	69.252	-	-
25	63	0.254592	0.054366	61.361	-	-

Table C.2: Technical data for Radius network